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WORKSHOP REPORT

Grand challenges for aerosol science and technology

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The Grand Challenges Workshop for Aerosol Science and Technology was organized for the International Aerosol Conference (IAC), in St Louis, September 2–7, 2018. The purpose of the workshop was to identify “Grand Challenges” for aerosol science and technology in the next decade and thereby indicate a viable research road map for the aerosol community.

The organization consisted of a committee of seven eminent aerosol scientists from around the world.[1] With their advice, ca. 70 distinguished aerosol scientists from around the world with interests spanning the sub-fields of aerosol science were invited to attend the workshop. All were asked to submit a single paragraph statement of a single most important grand challenge. In addition, a call was sent out to all members of all the aerosol societies across the world telling them about the workshop and inviting them to attend if they so wish.

Prior to the workshop, the submitted paragraphs were reviewed and organized. Then at the IAC meeting on Sunday, September 2, the workshop commenced with ∼150 attendees. A review of the paragraphs led to a dynamic and fruitful three-hour discussion. After the workshop and during the meeting, many impromptu discussions occurred among the conference attendees that refined the ideas that resulted from the workshop. A brief PowerPoint presentation describing the grand challenges that resulted from the workshop was presented Thursday, September 6, in a 1 h, plenary, open forum on the topic. The open floor was dynamic and led to very useful advice and comments that were recorded.[2] All these have been sources of the document presented here.[3]

Aerosols

The public knows that aerosols come out of spray cans and smoke stacks. However, sitting in a darkened room with sunbeams gliding through the windows, or observing rays of sun (crepuscular rays) projected through the clouds on an otherwise sunny day, alerts one to the fact that aerosols are more than spray cans and smoke stacks, and hints to the fact that aerosols are everywhere. Aerosols are dispersions of particles, either liquid or solid, in a gas; the particles in an aerosol span a wide range of sizes, compositions, and morphologies. Aerosols are, indeed, ubiquitous. The aerosols from smoke stacks, vehicle exhaust, indoor cooking, road-way dispersion and dust storms pollute our environment and do us harm. Premature death due to aerosols is a world-wide problem. On the other hand, aerosols are the synthetic pathway for many useful materials such as carbon black that makes tires remarkably durable, or titania that is the base material for essentially all paints manufactured today. Aerosols are also important in medicine to deliver drugs or detect illnesses; life makes aerosols. Both natural and human-made aerosols fill our skies and thereby affect the global environment as much as greenhouse gases but with much greater uncertainties.

So, there can be no doubt that aerosols are a major part of the human environment with significant effects for humanity. Therefore, it is essential that we scientifically study aerosols in their manifold situations and apply this science to deal with the technology of their applications and to protect us from harm.

The purpose of this summary report is to outline significant grand challenges for aerosol science and

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technology and thereby create a roadmap for future research. The grand challenges presented here are indeed "grand" and represent the most pressing issues for both the science and the technology of aerosols. We address both the areas where aerosols are typically referred to as "bad aerosols" and as "good aerosols", followed by a summary of the physical, chemical, and biological properties of aerosol that need to be addressed to cope with these challenges.

Environment

The aerosol community needs to develop a quantitative description of aerosols in the present, past, and future, over length scales from indoor and local through the global. This description must deal with the inherent complexity of aerosols in the environment and their multiple and many-dimensional impacts, including climate, visibility, ecosystems, as well as the numerous involved negative and positive feedbacks. This requires a better source apportionment of aerosols, such as discrimination between natural and anthropogenic aerosols, and quantification of the corresponding radiative forcings via aerosol–radiation interaction and aerosol–cloud interaction. The latter relates to the number of cloud condensation nuclei and ice nucleating particles (CCN and INP, respectively), i.e., particles that are able to form a cloud droplet/ice crystal at the given supersaturation in a cloud. As about 50% of these particles are not directly emitted but rather formed in the atmosphere from a variety of precursor gases, it is essential to understand the underlying processes. Research should give a special focus to the most vulnerable areas, such as the Arctic.

Health

The aerosol community needs to provide mechanistic links between aerosol chemical and physical properties with toxicity and biological end points. This will require the community to define the most important biological end points. A comprehensive ensemble of measurements will be required in order to link aerosol properties to physiological mechanisms that lead to those end points. Personal exposure must be differentiated from total integrated ambient concentrations, and dose from exposure. Measurements—both indoor and outdoor—need to provide sufficient spatial and temporal resolution to quantify exposure. These should include long-term measurements that can be used in connection with epidemiology studies, and that provide the data needed to establish links between aerosol properties and the physiological mechanisms that impact human health, extending beyond the commonly used approach of just PM10 or PM2.5 (particulate matter with an aerodynamic diameter smaller than 10 or 2.5 μm, respectively). The community needs to develop a methodology that is sufficiently simple and cost-effective, including accurate, cost-effective sensors, and then realize the potential scientific and societal benefits of networking these sensors and methods. Measurements are also needed that can evaluate long-term versus acute health effects in terms of toxicity. All of these studies need to be applied to understand the role of aerosols on the health of the individual in order to correlate/associate the links to end points. Finally, the community must effectively communicate the results of these studies to society.

The aerosol community needs to develop sound methods to detect and predict the spread of aerosol vectors of disease. This will enable appropriate agencies to take proactive measures to warn or protect the populous. To do this, massively distributed, yet affordable, measurement networks based on recent advances in molecular assay techniques are needed. Sampling of the ambient aerosols must occur across a wide range of scales and environments such as the home, schools, work-place, hospitals, and the surrounding communities.

The aerosol community needs to advance the state-of-the-art in sampling, detection, and analysis of exhaled breath biomarkers for disease, to monitor health.

Bioaerosols

A grand challenge for the aerosol community is to understand the influence of personal exposure to bioaerosols on long-term health. Important aspects of this challenge are how to determine personal exposure to bioaerosols within integrated exposure to indoor and outdoor agents. We don't know the dose–response curve for various microorganisms in different environments. We also don't know how modifications in human environments, such as urban pollution, feedback to alter the microbes via, for example, evolutionary pressure. Another important question is what role does cumulative exposure to aero-allergens play in chronic inflammation leading to other negative health outcomes?

The aerosol community needs to understand the roles of bioaerosols in the environment: the hydrologic cycle, cloud condensation and ice nucleation, and impacts on ecosystems such as crops, grasslands, and forests.

The aerosol community must seize the future and prepare for changes in biodiversity due to climate change and evolution of microorganisms. It must anticipate its primary role for understanding and controlling bioaerosols in space vehicles, and lunar or planetary installations.

Control technology

People spend most of their time indoors, and indoor air pollution is shortening lives world-wide. The aerosol community must provide the means to protect the public and ensure that people breathe healthy air. This challenge has multiple dimensions which should be pursued in parallel.

Filtration is the dominant method of removing particles from indoor air. It is a mature technology, but there are opportunities for improved filters through the use of new materials, and integration into filtration systems of additional functions such as gaseous and biological pollutant removal. The aerosol community must explore these opportunities to produce breakthroughs using nontraditional technologies.

The design of indoor environmental space typically follows slowly-developed codes and practices that do not incorporate the latest human health studies, or the latest knowledge on the patterns of indoor and outdoor pollutant sources. Narrowing the gap between engineering practice, cutting edge technology, and aerosol science to make smart building engineering and controls a standard practice is a grand challenge in itself.

Building occupants have a large degree of control over their indoor environment, but because the effects of air pollution are typically subtle and even imperceptible to most occupants, indoor air quality has a lower priority than it deserves. The aerosol community must accept the challenge to create innovative programs in education to enhance public awareness.

Materials

The aerosol community should aspire to be able to make any material at any scale. A simply stated but daunting goal is to create materials of arbitrary complexity with tailored properties of composition, size and shape. The ability to tailor, to control, to predict the results will need the combined efforts of laboratory experimentation and theoretical modeling. The community should explore and take advantage of developing artificial intelligence methods for mining the vast parameter space for product synthesis and process development. We should aspire to make stuff that our predecessors never dreamed of.

Making a desirable material at the lab bench is just the beginning; the challenge is then the scale-up to yield commercially significant products. Here the community must address a key tool that is presently lacking—the ability to measure aerosol properties, such as size distribution and temperature, space and time resolved, within the production reactor. This daunting challenge must often contend with high temperature, chemically reactive, and often corrosive flows, and mass loadings as high as 10%. Such data are essential for process control, addressing scale-up challenges, and for computational-fluid-dynamics-reaction-aerosol coupled modeling for process optimization.

Finally, we must not forget that the aerosol community must be responsible for their science. Hence life-cycle analysis, toxicity, and environmental impact analysis of new materials must be performed.

Physics and chemistry

The aerosol community must bring together physical and chemical experiment and modeling to better understand a broad variety of fundamental issues. It is important to stress that communication between modelers and experimentalists is essential for rapid and relevant progress.

There is a significant need to develop a viable description of light scattering and absorption by particles of any size, shape, and composition. This need arises because many ambient aerosols, as well as aerosols found in materials manufacturing processes are non-spherical and can have complex, heterogeneous morphologies, and can even contain multiple phases. Perhaps the most significant use of such knowledge is to quantify the impacts of aerosols on the radiation budget of the Earth and, thereby, determine aerosol impacts on global warming. This need applies to other applications including optical remote sensing of ambient aerosols, especially via satellites, and calculation of atmospheric visibility and visibility impairment. In the manufacturing realm another important application is for real time, *in situ* measurements of aerosols in process flow streams during materials production. In this regard, as highlighted in the Materials section of this report, the problem of optical diagnostics of aerosols with high mass loading, on the order of 10%, where multiple scattering leads to confusion, is an important impediment that needs to be overcome.

Another grand challenge is the need to develop a viable understanding of particle nucleation and growth, spanning the transition from molecules, to clusters, to stable condensed-phase materials. This growth transition is made very complex by the fact that the physical and chemical properties of the evolving entities are changing with size. A fundamental understanding of the growth transition would be the backbone on which to support the advancement of many related applications, namely air pollution chemistry, cloud formation, species transport and diffusion, particle formation, human health related toxicology and materials synthesis.

As alluded to in the paragraph above, there is a significant need at the fundamental level to develop a viable understanding of the evolution of physical and chemical properties of particles in the transition from the atomic/molecular to “bulk” particle scales. New sciences lies in this intermediate realm, and as most of us are aware, we live well today based on the new science of yesterday.

Overarching grand challenge

While simple metrics of an aerosol, whether number concentration, mass concentration, PM2.5, or some other measure yet to be defined, may be useful for specific applications, multidimensional characterization of aerosols is needed to understand their complex effects throughout all the areas reviewed above. Regulatory agencies often seek a single measure, such as $PM_{2.5}$, but no single parameter can describe all of the effects of concern which often result via a synergy of properties. Thus, an overarching need for aerosol science in general is to advance the art of aerosol measurement and apply this art for multidimensional characterization.

Many of the above activities will result in a vast amount of data that must be openly accessible and rigorously preserved in perpetuity. Perhaps the best way to ensure this preservation is to engage the only institutions that have, as their primary mission, preservation of knowledge for the long term—Libraries.