USING NANOTECHNOLOGY TO ACCELERATE THE WATER CONDENSATION NUCLEATION AND GROWTH FOR RAIN ENHANCEMENT

Project Final Report

UAE Research Program for Rain Enhancement Science

Reporting Period (Interim September Report)	
Start Date	13 January 2016
End Date	1 July 2019
Submittal Date	1 September 2019
Khalifa University of Science and Technology	
Principal Investigator	Professor Linda Zou

EXECUTIVE SUMMARY

1. Summary of Scientific and Technical Progress vs. Plan:

The UAE Rain Enhancement Science Program (UAEREP) has awarded its first cycle of projects in January 2016, until now 9 projects have been awarded after the comprehensive international competitive evaluation process. The project "USING NANOTECHNOLOGY TO ACCELERATE THE WATER CONDENSATION NUCLEATION AND GROWTH FOR RAIN ENHANCEMENT" has been successfully awarded in the 1st Cycle, led by Principal Investigator Prof Linda Zou, Khalifa University of Science and Technology, Abu Dhabi, UAE. This project based the thermodynamic principles and interfacial and surface science, using nanotechnology know-how to design the nanostructured cloud seeding materials, which aimed to have significant impact in water condensation and collision-coalescence for warm clouds, and nucleation and crystal grow for colder clouds. At the completion of this 3.5 years' project, all the milestones mentioned in the proposal have been well achieved: 1) core/shell structured particles with TiO_2 nanoparticles coated on the NaCl crystals (CSNT) have been designed and synthesized, the synergistic effect of the hydrophilic TiO_2 shell and hygroscopic NaCl core has demonstrated to enhance the condensation and water droplet formation and growth; 2) nanostructured particles through bioinspired gradient-driven mechanism as cloud condensation nuclei have been designed and synthesized; 3) novel ice nucleation seeding particles have been designed and synthesized for facile ice nucleation; 4) methods for real time observation by ESEM for evaluation of water vapor and nanocomposite interactions have been developed and used to evaluate the materials' characteristics; 4) both 1D and 3D numerical models have been developed for evaluation of the effects of the novel cloud condensation nuclei on rain enhancement. The "ground-breaking" research outcomes have been published at high impact journals, 1 international patent applications, and 2 more provisional patents. This project has been evaluated by the Scientific Direction Committee of UAEREP in their feedback letter of the latest project progress report as follows: "This has been an extremely successful project, both in terms of the scientific and technical achievements, but also in shedding light on how innovative technologies (in this case nanotechnology) can provide exciting new potential to the development of seeding material for rainfall enhancement. As an important additional task of the original project proposal, scale up of the production of the CSNT particles have been trialed and pivotal achievement have been made. Overall, this project led by Prof Linda Zou played a great role in helping to establish and affirm the scientific strategies and visions of UAEREP, i.e. to showcase the world class research capacity of UAE faculty at the lead science and technology university in Abu Dhabi, UAE, and consolidate UAE as one of the leaders in innovation of cloud seeding materials science. Further support to PI (Prof Lidna Zou) after the project completion is needed to deliver deeper impact created by the research project outcomes on the rain enhancement field globally.

SCIENTIFIC AND TECHNICAL PROCESS

Highlights of the project:

At the end of the 3.5 years of project period, all of the planned project activities have been fully achieved: core-shell nanostructured TiO_2/NaCl (CSNT) particles have been designed and fabricated as cloud condensation nuclei; bio-inspired water absorbing and collecting hydrophilic/ hydrophobic particles have been designed and fabricated; a real time observation and evaluation method of water condensation and crystallization on nanocomposite cloud seeding materials have been developed and used in the project; numerical modeling (1D and 3D) for evaluation of the effects of the novel cloud condensation nuclei on rain enhancement have been developed by the subcontractor based on the data provided by PI Zou: 3D rgraphene nanosheets enhanced ice nucleation particles have been designed and fabricated. As an additional task, scale up production of CSNT particles have been conducted and sufficient quantity of coated CSNT particles are ready for cloud seeding field operation trials.

Updated project Gantt chart

Planned Activities	Year 1				Year 2				Year 3				Year 4	
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2
Design and fabricate cloud condensation nuclei by a salt/TiO2 core-shell nanoparticles														
Design and fabricate bio-inspired water absorbing and collecting superhydrophilic/ hydrophobic particles														
Design and fabricate graphene nanosheets enhanced ice nucleation particles (extension is needed at the end of the project)														
Develop methods for real time observation and evaluation of water condensation and crystallization on nanocomposite CCN														
Develop a numerical modeling for evaluation of the effects of the novel cloud condensation nuclei on rain enhancement														
Recommend the optimized nanocomposite CCN and their trials in open system, final project report														

Task: Design and fabricate cloud condensation nuclei by a salt/TiO_2 core-shell nanoparticles.

It was first time that nanotechnology approach was employed to enhance the rainfall by cloud seeding methods, which novel sub-micron hygroscopic cloud seeding materials were designed and fabricated. The developed nanoparticles had a core-shell structure of NaCl coated with a thin layer of TiO_2 nanoparticles (CSNT). The addition of TiO_2 in the surface shell layer allowed the hygroscopicity of the composites to be improved. The hydrophilic TiO_2 helped to increase the

interfacial water vapor pressure so as to reduce the hydroscopic point of the composites. This experimental result suggested that novel NaCl/TiO_2 nanocomposite particles can adsorb water vapor efficiently and form larger water droplets leading to rain fall. This outcome was considered as patentable intellectual property. 1 world patent has been filed, 1 high quality high impact journal article has been published, and PI Zou has been invited to speak at 2 high impact nanomaterials conference in USA and in KAUST.

Task: Design and fabricate bio-inspired water absorbing and collecting superhydrophilic/hydrophobic particles.

Inspired by the water-vapor harvesting system of desert beetles with the alternating hydrophilic/hydrophobic surface microstructure, we have designed and fabricated bio-inspired water absorbing and collecting particles as cloud seeding materials. A novel type of graphene/NaCl (GN) particles were successfully synthesized by using self-assemble co-crystallization technique to slightly coat partially reduced graphene-oxide (rGO) plates on NaCl crystal. The particles could deliquesce at lower environmental than NaCl, and form larger water droplets, in-situ visual observation under E-SEM. Samples have been sent to collaborator's lab for conducting cloud chamber experiments. The research outcomes include: 1 provisional patent has been filed, 1 high quality high impact peer reviewed journal article has been published.

Task: Develop numerical modeling for evaluation of the effects of the novel cloud condensation nuclei on rain enhancement

One dimensional Model for Cloud Seeding Experiments (1D MCSE) which is based on Microphysical and 1 D Convective cloud model was developed first, then 1D version of Model for Cloud Seeding Experiments (1D MCSE) was incorporated to 3D version (3D MCSE). Novel seeding materials water vapor interaction results were used as input for the 3D MCSE model. Modeled cloud under considered conditions represent real cloud dynamics. The 3D modelling simulation demonstrated that CSNT particles could be particularly efficient seeding materials in arid climates characterized with a scarcity of water vapor. The research outcomes: 2 paper published in high quality peer reviewed journals

Task: Scale up trials of core/shell TiO_2/NaCl cloud seeding materials

[confidential]

Task: Design and fabricate 3D graphene enhanced ice nucleation particles.

There is a need and strong interesting internationally for developing ice-nucleating particles, which can initiate ice nucleation at higher temperatures and promote fast crystal growth. We aim to synthesize nanostructured composite materials for ice nucleation in cold cloud offering excellent in-plane and out-of-plane properties that are in favor of ice nucleation of supercooled water. We have designed and synthesized a 3-dimensional reduced graphene oxide (3D-rGO) and silica dioxide (SiO_2) nanocomposite material. In this composite, SiO_2 can enhance the overall water molecule adsorption capabilities of the composite and enable less aggregation of the overall 3D-rGO structure, thus leading to more available sites for ice nucleation, whereas 3D-rGO acts as templates for ice crystal growth due to its hexagonal lattice structure, with the ability to dissipate the latent heat produced by ice condensation rapidly. ESEM image and video have clearly demonstrated facile ice nucleation and rapid ice crystal growth on both microporous site of the nanocomposite materials (Fig 1). The composite material was found to accelerate the deposition nucleation of ice crystals and rapid growth. In addition, ice nucleation measurement was measured at a large cloud chamber hosted at KIT (Germany), the indicative results showed that this material (3DrGO/SiO_2) can immediately initiate ice

nucleation and showed strong growth of ice particle numbers over time, due to the heavy commitment of the cloud chamber by series of EU based aerosol campaigns, no results can be provided by KIT at this stage due to limited time and personnel. If UAEREP can provide further funding, an experimental plan can be prepared and implemented with paid contract via KIT and KU collaboration.

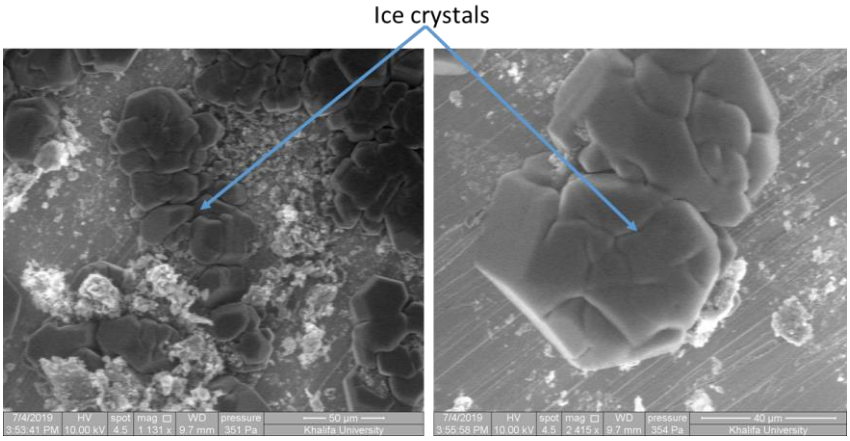

Fig 1. Ice nucleation and growth on microporous site of the nanocomposite material at -8ºC, 8% supersaturation. (Please note, in the absence of nucleation particles, water can remain as supercool down to −40 °C before freezing to ice).

PUBLICATIONS/PRESENTATIONS

Publications

1. H Liang, MT Abshaev, AM Abshaev, BM Huchunaev, S Griffiths, L Zou, Water vapor harvesting nanostructures through bioinspired gradient-driven mechanism, Chemical Physics Letters 728, **2019** 167-173

2. M Ćurić, M Lompar, D Romanic, L Zou, H Liang, Three-Dimensional Modelling of Precipitation Enhancement by Cloud Seeding in Three Different Climate Zones, Atmosphere 10 (6), **2019**, 294

3. M Lompar, M Ćurić, D Romanic, L Zou, H Liang, Precipitation enhancement by cloud seeding using the shell structured TiO2/NaCl aerosol as revealed by new model for cloud seeding experiments. Atmospheric Research, **2018,** 212(November), Pages 202-212.

4. Y. Tai, H. Liang, N. El Hadri, A. M. Abshaev, B. M. Huchinaev, S. Griffiths, M. Jouiad, and L. Zou, Core/Shell Microstructure Induced Synergistic Effect for Efficient Water-Droplet Formation and Cloud-Seeding Application. ACS Nano, **2017**, *11* (12), pp 12318–12325.

Presentations at Conferences

5. L Zou, Core/shell structured novel cloud seeding materials for rain enhancement. Nano-Enabled Water Technologies Conference organized by King Abdullah University of Science and Technology (KAUST), KSA. 28-30 January, 2019

6. L Zou, Core/Shell Microstructure Induced Synergistic Effect for Efficient Water Droplet Formation and Cloud Seeding Application. Materials Research Society (America) 2018 Spring Meeting, Symposium EN11: Nanomaterials for the Water and Energy Nexus in Phoenix, Arizona, USA, April 2-6, 2018.

7. PI Zou and the team has represented Khalifa University attended the display at Abu Dhabi Sustainability Week in January 2017.

8. PI Zou has agreed to represent Khalifa University attending the display at World Energy Congress to be held in Abu Dhabi in September 2019.

Invention Disclosures/Filed Patents

- **New this Reporting Period**

1. USA Provisional Patent Application Serial No. 62/791,927. "3D Reduced graphene oxide/ SiO_2 for cold cloud ice nucleation" has been filed on January 14, 2019.

2. USA Provisional Patent Application Serial No. 62/406,414. "Coated Chloride Salt Particles and methods of Making and using the same" October, 2016

3. USA Provisional Application Serial No. 62/616,759. "Sodium chloride/graphene particles and methods" has been filed on January 12, 2018,

OTHER INFORMATION

Any additional brief summary information or discussion that the team feels useful and important to include can be added as a section here. That might include, for example, reflection on the importance and impact of the research, or discussion of new initiatives to broaden the funding base (e.g., recruit external funding) for the research.

The final project report which is due on 1 September will be my last commitment as PI according to the project agreement. After that I am not in the position to take any new tasks and request from NCM or SDC of UAEREP. If more work or response is required from my, please consider to make a new arrangement, such as contracted consultant or provide next stage funding for project or research center to enable my time/effort for any further involvement.

REFERENCES

APPENDICES (IF ABSOLUTELY NECESSARY)