Particle Technology Working Group (PTWG) for Global Collaboration on High-Temperature Solar-Thermal Particle Research

Clifford K. Ho[1, a)]

[1]*Ph.D., Sandia National Laboratories, P.O. Box 5800, MS-1127, Albuquerque, NM 87185-1127, USA*

[a)]Corresponding author: ckho@sandia.gov

Abstract. This paper provides a summary of the activities of the international Particle Technology Working Group (PTWG). The PTWG was formed to initiate global coordination among high-temperature solar-thermal particle researchers and increase collaboration, create a shared database, avoid duplication, accelerate technology development, and provide a stronger basis for funding opportunities in particle research with a greater return on investment. The PTWG consists of over 40 researchers from 13 countries working on high-temperature solar-thermal particle technologies that include power generation, thermochemistry, solar fuels, thermal storage, and process heat. Results include the first international PTWG workshop held in Riyadh, Saudi Arabia, the formation of a PTWG website, and the successful development of a large international proposal to develop next-generation concentrating solar power technologies using particles as the heat-transfer and storage media.

INTRODUCTION

Particles can be used to store and convert solar energy for multiple applications including electricity production [1], process heat and manufacturing [2], and thermochemistry/fuels production [3]. For electricity production, the use of inert particles such as sintered bauxite or sand has significant advantages over the use of conventional molten nitrate salts, including greater range of operating temperatures (subzero to >1000 °C vs. ~200°C – 600 °C), low costs, low corrosion effects, and no need for air-tight seals [4]. Reactive particles such as ceria can be used in two-step reduction/oxidation processes to create synthetic fuels and hydrogen to supplant fossil fuels [5]. Heated particles can also be stored efficiently and inexpensively for long periods in low-cost storage bins for dispatchability and on-demand use [6].

Although a great deal of high-temperature solar-thermal particle research is occurring internationally, very little coordination has existed, especially across applications, leading to potential duplication of efforts and limited knowledge sharing or collaboration. The international Particle Technology Working Group (PTWG) was formed to initiate coordination among particle researchers in SolarPACES to increase collaboration, create a shared database of particle research, avoid duplication, accelerate technology development, and provide a stronger basis for funding opportunities with a greater return on investment. The PTWG spans research in SolarPACES Task 1 (Solar Thermal Electric Systems), Task II (Solar Chemistry Research), Task III (Solar Technology and Advanced Applications), and Task IV (Solar Heat Integration in Industrial Processes). This paper summarizes efforts of the PTWG, including an overview of the first PTWG workshop, current research among PTWG members, and joint research opportunities and needs. It also describes the process of establishing the PTWG and receiving funding from SolarPACES to serve as a model for other potential collaborative working groups and task areas within SolarPACES.

APPROACH

Formation of the PTWG

During the 2016 SolarPACES conference, Sandia National Laboratories (Cliff Ho) and DLR (Reiner Buck) proposed the concept of the PTWG to the SolarPACES Task 1 Lead (Mark Mehos). A brief presentation was made to discuss the value proposition of the PTWG and to establish tasks, budget, timeline, and deliverables for the project. The Task 1 Lead then proposed the idea to the SolarPACES secretariat (Christoph Richter) and the SolarPACES Executive Committee. The PTWG was approved, and a total of $50K was allocated to the PTWG: $30K to cover travel expenses for attendees from member countries to attend a workshop, and $20K for the principal investigator (Cliff Ho) to initiate the PTWG, coordinate the workshop, compile results, and publish a final report and website.

New SolarPACES Task Proposal Process

Since the formation of the PTWG, SolarPACES has implemented a formal procedure for funding Task proposals. Proposals to one of the SolarPACES Task Areas must (1) be related to the goals and scope of the Task area, (2) benefit members of SolarPACES, and (3) not likely be funded from normal sources. The proposal must be sponsored by an operating agent or executive committee (ExCo) member of SolarPACES and include a minimum of three member countries. Only member countries can receive funding, and funding is limited to 150 k€ per proposal. Proposals must be submitted at least four weeks prior to an ExCo meeting, which occurs in the fall during the annual SolarPACES conference and again in the spring. Proposals consist of a title, team, abstract, background, work plan, schedule, milestones, deliverables, goals, and budget. Review criteria include eligibility, relevance to Task area, scientific merit and clarity of objectives, potential impact and benefits, work plan, and appropriateness of budget. The projects can last up to 18 months, with a potential no-cost extension of 6 months. A final report is due at the end of the project.

RESULTS

PTWG Workshop

A series of teleconferences and web-based meetings were held in late 2016 and 2017 to initiate the working group, introduce and familiarize the team with each other, and to coordinate the international PTWG workshop. The coordination meetings and activities culminated in a two-day workshop held in Riyadh, Saudi Arabia, on April 19 – 20, 2017, sponsored by SolarPACES and the Saudi Electricity Company (SEC). Researchers from 13 institutions and 10 countries participated in the workshop (**FIGURE 1**).

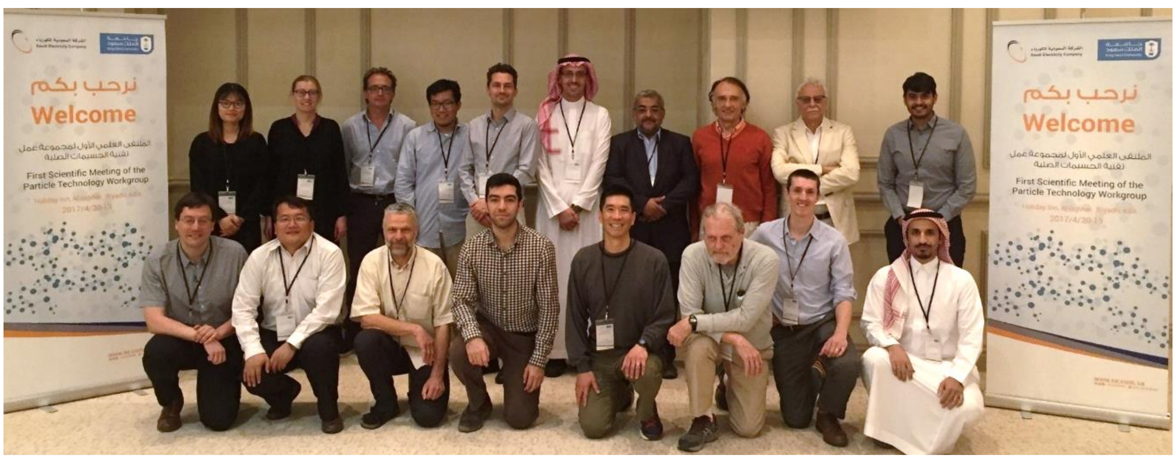

FIGURE 1. Researchers from 13 institutions and 10 countries participated in the first international Particle Technology Working Group workshop in Riyadh, Saudi Arabia, April 19 – 20, 2017.

The first day consisted of opening remarks from SEC and King Saud University, who expressed their strong support for solar-thermal particle-based technologies and their interest in deploying a commercial particle-based concentrating solar power (CSP) plant. Brief technical presentations were then made by each of the researchers to summarize their particle research. The second day began with a tour of the 300 kW_t falling-particle CSP system at King Saud University. Small groups were led through the major components, including the heliostat field, receiver at the top of the tower, storage, heat exchanger, and air-Brayton power cycle. The remainder of the day was devoted to identifying potential collaborations and joint research in small breakout groups.

Summary of Workshop Abstracts and Presentations

Abstracts and presentations from the PTWG workshop are available on the SolarPACES website: http://www.solarpaces.org/solarpaces-particle-technology-working-group/. A summary of the abstracts and work being performed by each participant is provided below (ordered alphabetically by country).

University of Adelaide, Australia. Researchers at the University of Adelaide have developed advanced diagnostic methods to better characterize and understand heat transfer and hydrodyamics of particle-laden flows [7-9]. Laser-diagnostic methods are used to evaluate particle velocity and number density, and laser-induced thermo-phosphoresis is used to measure the temperature of individual particles in suspension. Wind and water tunnels are also used to better understand convective heat loss from cavity receivers. A novel particle vortex receiver/reactor has been developed to heat particles for solar thermochemical processes such as alumina calcination and gasification [10].

Abstract Title: "Advancing understanding of heat transfer and performance of suspension-flow particle reactors of both novel and general solar thermal technologies"

Contributors: G.J. 'Gus' Nathan, Tim Lau, Woei Saw, Peter Ashman, Mehdi Jafarian, Maziar Arjomandi, Philip van Eyk, Bassam Dally, Alfonso Chinnici, Zhao Tian, Zeyad Alwahabi.

CSIRO Energy, Australia. Researchers at CSIRO have developed a 5 m tall experiment to investigate particle hydrodynamics relevant to a high-temperature falling particle receiver system. Design parameters such as capacity, geometry, dimensions, flow rate, and particle properties can be investigated to evaluate particle dispersion and potential for solar energy absorption. Detailed modeling of particle hydrodynamics and heat transfer is also being performed [11-13].

Abstract Title: "Design considerations for free falling particle receivers and experimental set-up for 5 m falling test"

Contributors: Jin-Soo Kim, Apurv Kumar, Wilson Gardner, William Yang, Cliff Ho

TU Wien, Austria. Researchers at TU Wien have been working since 2011 on a particle-based thermal energy storage system [14-18]. The system consists of a counter-current fluidized bed heat exchanger with minimum solids inventory and low auxiliary power requirements. Two test rigs and three cold-test installations have been developed. The largest rig has a thermal capacity of 200 – 280 kW_t with 1 MWh of energy and a maximum operating temperature of 390 °C due to the use of thermal oil. The current particle material is 80 μm sand.

Abstract Title: "Development of a particle based heat exchange and storage system suitable both for CSP and for other TES-applications such as ACAES and power plant flexibilisation"

Contributors: Markus Haider, Karl Schwaiger, Peter Steiner, Heimo Walter

Key Laboratory of Solar Thermal Energy and Photovoltaic Systems, Institute of Electrical Engineering, Chinese Academy of Sciences, China. Researchers are investigating a new quartz-tube solid-particle air receiver [19-21]. The particles are irradiated by concentrated sunlight and fluidized within the quartz tubes by air, which is heated as it flows through the particles. Experiments have been performed that have achieved air temperatures of ~870 °C with thermal efficiency of 78%. Studies are being performed to optimize design parameters such as particle size, aperture area, and tube material.

Abstract Title: "Experimental Study of a Quartz Tube Solid Particle Air Receiver"

Contributors: Fengwu Bai, Zhiying Cui

PROMES-CNRS, France. Researchers at PROMES-CNRS are investigating a new particle-in-tube concept where a dense suspension (30 – 40% solids volume fraction) of 50-60 μm particles flows upward through opaque tubes using fluidization with low air velocities on the order of centimeters per second [22-26]. The system is different than circulating fluidized beds where the air velocity is on the order of 10 m/s with a particle volume fraction less than 5%. A 150 kW_t multi-tube receiver system was tested on-sun, and a 4 MW_t system capable of heating particles to 800 °C is being constructed atop the Themis solar tower, along with a two-tank particle storage and particle-to-pressurized air heat exchanger coupled to a 1.2 MW_e gas turbine.

Abstract Title: "The particle-in-tube concept for concentrated solar energy conversion at high temperature"

Contributors: Gilles Flamant

DLR, Germany. Researchers at DLR have investigated several particle receiver technologies, particle heat exchangers, thermal storage, and particle abrasion and attrition [27-31]. Particle receiver designs include face-down falling particle receiver modeling and centrifugal receiver design and testing. The centrifugal receiver uses a rotating cylindrical cavity that causes the particles to adhere to the walls by centrifugal force while being heated by concentrated sunlight entering through an aperture. A 10 kW prototype successfully heated particles up to 900 °C, and a 500 kW system was also tested at solar tower Juelich. A rotary kiln receiver has also been studied for thermochemical applications. Particle flow and heat transfer through a shell-and-tube heat exchanger was studied by both experimentation and modeling. Erosion studies of high-temperature alloys by moving particles were also studied.

Abstract Title: "Particle receiver and system development at DLR: status and perspective"

Contributors: Miriam Ebert, Reiner Buck

IRC-CNR, Italy. Researchers at IRC-CNR are investigating (1) effective collection of concentrated solar radiation using dense gas-fluidized particle beds, (2) enhanced heat transfer of the incident power through the bed and to immersed heat-exchanger surfaces, and (3) effective energy storage in the particle bed with consideration of inherent transients in incident power [32-39]. A novel concept employing fluidized-bed compartmentalization with indirect irradiation was proposed and a pilot-scale facility based on the concept was demonstrated in Sicily. Directly irradiated fluidized beds were also investigated, and processes such as bubble bursting, sintering, and applications of carbonation/calcination thermochemical cycles have been studied.

Abstract Title: "Fluidized beds for concentrated solar power with thermal/thermochemical energy storage"

Contributors: Roberto Solimene, Piero Salatino, Paola Ammendola, Riccardo Chirone

King Saud University, Saudi Arabia. Researchers at KSU have designed, developed, and tested a 300 kW_t particle receiver system at the Riyadh Techno-Valley near the KSU campus that includes a discrete-structure particle heating receiver, particle storage, particle heat exchanger, and 100 kW_e gas turbine [6, 40-43]. The fully integrated high-temperature solar gas turbine system is being demonstrated with unique support structure for the gas turbine that minimizes high-temperature and moderate-pressure piping. Other structural, mechanical, and electrical systems, controls, and instrumentation have been implemented. Cost-effective materials and designs for the particle storage system have also been identified.

Abstract Title: "Discrete structure particle heating receiver technology and related concentrator solar power developments at king saud university in collaboration with georgia tech"

Contributors: Hany Al-Ansary, Abdelrahman Elleathy Said Abdel-Khalik, and Sheldon Jeter

IMDEA Energy Institute, Spain. Researchers at IMDEA are developing particle-based thermal storage systems to enable wider temperature ranges and avoid problems such as freezing [44-47]. The particle storage can be coupled to a wide range of heat-transfer fluids heated in the receiver (air, particles, CO_2, steam, molten salt, thermal oil) and power cycles (supercritical CO_2, combined cycles). Various coupling options have been studied, including subcritical and supercritical Rankine and supercritical CO_2 Brayton cycles.

Abstract Title: "Integration of particle-based systems in central receiver solar power plants"

Contributors: J. González-Aguilar, M. Romero

Middle East Technical University, Turkey. Researchers at METU have been studying solid particle receiver designs using gravity-driven, dense granular flow as opposed to fluidized or falling particles [48, 49]. Both vertical tubes and vertical parallel plates have been studied. Experiments were performed to evaluate the effective thermal conductivity of the flowing sand. Data was used as input to a 5 m x 5 m finned solar-receiver computational model. Different geometries and irradiance values were investigated, and thermal efficiency and peak temperature were modeled. Particle storage systems employing an array of rectangular tubes with flowing air were also studied for coupling to closed-air Brayton cycles.

Abstract Title: "Experimentation and modeling of a dense granular flow receiver and CFD modeling of a fluidized sand bed for thermal energy storage"

Contributors: Evan Johnson and Serdar Hiçdurmaz

Masdar Institute Solar Platform, UAE. Researchers at Masdar Institute have studied the use of desert sand as a sensible thermal energy storage material [4, 50-52]. Samples were collected from different locations of the UAE desert, and thermal and mechanical properties were measured. The samples were thermally stable from ~650 – 1000 °C. At higher temperatures, agglomeration occurred. Optical properties were also measured, and transformation of calcium carbonate into calcium oxide was found to reduce the solar absorptivity.

Abstract Title: "Desert sand characterization for high-temperature particle solar receiver"

Contributors: Nicolas Calvet

Georgia Institute of Technology, USA. Researchers at Georgia Tech has completed several projects related to the Discrete Structure Particle Heating Receiver and other technologies related to CSP and solar thermochemistry [53-59]. Most of these projects were performed in collaboration with researchers from King Saud University (KSU) and Sandia National Laboratories. KSU and Georgia Tech have designed and developed a 300 kW_t solar tower at the Riaydh Techno Valley that includes a full particle-based CSP system. Studies have included heat transfer in particle heat exchangers, durability of flowing particles, efficiency of particle receiver designs, design of particle lift systems, and design of systems for thermochemical storage.

Abstract Title: "Discrete structure particle heating receiver and related concentrator solar power research at the Georgia Institute of Technology"

Contributors: Said Abdel-Khalik, Matt Golob, Clayton Nguyen, Sheldon Jeter, Kenzo Repole, Matt Sandlin, Ramy Imam, Lucy Shen, Hany Al-Ansary, and Abdelrahman Elleathy

National Renewable Energy Laboratory, USA. Researchers at NREL have been studying solid particles as the heat transfer and storage medium of CSP plants since 2011 [60-65]. Components in the particle thermal system that have been studied include the particle receiver, thermal energy storage, and heat exchanger. A novel solar receiver has been proposed that uses solar-absorbing tubes or cavities formed by an array of absorbers that allow flow of particles in the enclosures. The cavities formed by the array of absorbers increase solar absorptance and decrease thermal losses.

Abstract Title: "Development of particle-based concentrating solar power system at NREL"

Contributors: Zhiwen Ma

Sandia National Laboratories, USA. Researchers at Sandia have evaluated solar thermal particle technologies for power production and thermochemical applications [66-94]. A 1 MW_t continuously recirculating falling particle receiver was tested on-sun using both obstructed and free-falling particles. Particle temperatures up to 800 °C were recorded with particle mass flow rates of ~1 – 7 kg/s and average irradiances up to 1,000 suns. Thermal efficiencies ranged from 60 – 70% for free-falling particles and up to 80% for obstructed flow tests. A Cascading Pressure Reactor was designed and tested that uses metal oxides or other particles as the redox material for two-step thermochemical H_2O or CO_2 splitting. The particles also serve as the medium to enable a 1000-fold pressure ratio between the thermal reduction and oxidation steps.

Abstract Title: "High-temperature particle receivers and reactors for concentrating solar power and thermochemical fuel production"

Contributors: Clifford K. Ho and Ivan Ermanoski

Workshop Recommendations

During the breakout sessions of the PTWG workshop and follow-on discussions, a number of research needs and opportunities were identified. Table 1 summarizes the research topics, needs, and opportunities for international collaboration.

Table 1. Summary of research needs and opportunities for particle technology collaboration.

Research Area	**Needs and Opportunities**
Particle Receiver	• Design and testing of configurations to reduce radiative and thermal losses, especially at high temperatures (> 700 °C for next-generation CSP and > 1000 °C or higher for solar thermochemical applications) • Development of in-situ particle mass flow measurement techniques • Identification of low-cost materials and construction with high durability • Mitigate impacts of external wind and fluctuations in solar irradiance • Particle distribution and conveyance within the receiver • Simulation methods and tools for dense-phase particle flows
Particle Storage	• Simulation and testing of heat loss from particle storage bins • Identification of low-cost materials and features to insulate particles while maintaining structural integrity • Design and demonstration of transient charging and discharging mechanisms with minimal heat loss • Demonstration of pilot-scale latent and thermochemical energy storage methods • Designs for large-scale capacities (10 – 100 MW_e)
Particle Heat Exchanger	• Characterization and optimization of particle/wall heat transfer • Particle flowability at high temperatures • Evaluation of material erosion, fatigue, and creep • Design for manufacturability and reliability • Controls, designs, and features to minimize start-up times and excessive thermomechanical stresses • Evaluation of materials and designs to lower costs while maintaining required performance
Particle Conveyance	• Design of high-efficiency/low-friction conveyance methods that operate at high temperatures • Reliable operation at mass flow capacities for large (~100 MW_e) CSP plants (~1000 kg/s) • For thermochemical applications, reliable conveyance at temperatures > 1000 °C and higher • Improved understanding of friction coefficient as a function of temperature and materials (particle and containment materials)
Particles	• Thermophysical property characterization at various temperatures and flow conditions • Attrition mechanisms and dust formation • Reduction of material erosion • Identification of low-cost materials with desirable optical/thermal/physical properties
Systems Analysis	• Technoeconomic analyses using hierarchy of modeling and inclusion of uncertainty (probabilistic modeling) • Controls and instrumentation; transient operation and startup/shutdown procedures
Modeling	• Development of high-fidelity particle flow models at a range of solids volume fractions (from dilute to dense phase) • Development of tools and methods to incorporate coupled optical/thermal/fluid/chemical processes • Validation of models with experimental data; development of database of data and models • Integration of high-fidelity models with lower-fidelity systems models

Proposals and Collaborations

The efforts of the PTWG have resulted in several joint proposals, including a major proposal to the U.S. Department of Energy's (DOE) Gen 3 CSP Funding Opportunity Announcement to develop a next-generation CSP plant using particle-based technology (https://www.energy.gov/eere/solar/generation-3-concentrating-solar-power-systems-gen3-csp). The $45M proposal ($35M from DOE, ~$10M cost share from international partners), titled "Gen 3 Particle Pilot Plant (G3P3): Integrated High-Temperature Particle System for CSP," consisted of numerous international participants from the PTWG, including Sandia National Laboratories (USA), National Renewable Energy Laboratory (USA), Georgia Institute of Technology (USA), King Saud University (Saudi Arabia), CSIRO (Australia), University of Adelaide (Australia), Australian National University (Australia), CNRS-PROMES (France), and DLR (Germany). The proposal was awarded ~$10M from DOE for the first two years of the proposed five-year project to de-risk remaining challenges associated with G3P3 technology, and may receive an additional $25M if selected for construction and operation of the proposed particle pilot plant for the remaining three years. The G3P3 project is expected to begin in October 2018 and will design a 1 – 10 MW_t particle pilot plant that will heat particles to nearly 800 °C with 6 hours of storage for power generation via advanced high-temperature power cycles. The G3P3 system consists of a particle receiver (irradiated by a heliostat field), storage, particle-to-working-fluid heat exchanger, and particle lift system that will operate for thousands of hours with demonstration of startup, shutdown, and deferred storage.

Other proposal opportunities were identified by the PTWG and are outlined below:

- **Australia**: Phase 2 of ASTRI program being negotiated; large potential for particle research
- **China**: Currently interested in pilot plant and demonstration facilities; some open opportunities for fundamental research
- **Europe**: European Commission – DLR and others are submitting proposals to create opportunities for particle research; PROMES-CNRS has proposal with H2020 *Next-CSP* project for dense-suspension particle-in-tube receiver project
- **Saudi Arabia**: National Plan for Science and Technology – first phase of a 5-year program, technology acceleration program (similar to SunShot but includes broader spectrum of technologies); opportunities for foreign partners
- **UAE**: Masdar Clean Energy may have funding for high impact CSP research
- **USA**: DOE funding (Gen 3) for CSP and particle research; ongoing DOE Solar Energy Technology Office funding for more basic research in CSP; some funding for thermochemical processes is possible

Website and Information Sharing

A website has been established to maintain and promote communications among the PTWG and the rest of the SolarPACES community (http://www.solarpaces.org/solarpaces-particle-technology-working-group/). The website is also intended to serve as a repository for data that can be shared among particle researchers for experimental testing and model validation. Key elements of the website consist of the following: Problem Statement, Value Proposition, Objectives, Advantages of Particle-Based Systems, summary of the PTWG workshop, PTWG Share (links to relevant files and data), and contact information.

A spreadsheet was compiled that summarizes the institutions, countries, and researchers currently within the PTWG. Contact information and a brief description of the research being performed by each institution is included in the spreadsheet to foster communication and collaboration, and the spreadsheet is available on the PTWG website. Relevant information (literature, data, models) pertaining to solar thermal particle technology that researchers would like publicly posted to the PTWG website should be forwarded to the author.

CONCLUSIONS

The PTWG, with initial funding from SolarPACES, has over 40 researchers from 13 countries working on high-temperature solar-thermal particle technologies that include power generation, thermochemistry, solar fuels, thermal storage, and process heat. The first international PTWG workshop was held April 19 – 20, 2017, with sponsorship from the Saudi Electricity Company. Current research activities were presented, and breakout groups were formed to discuss opportunities for collaboration and research needs. Several joint proposals have been submitted that take advantage of the PTWG collaboration. Also, a SolarPACES website has been established to maintain and promote communications, information sharing, and collaboration opportunities. The PTWG can serve as a model for other collaborative and cross-cutting working groups within SolarPACES.

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