Institutional Abstracts

Particle Technology Working Group (PTWG) Workshop

Riyadh, Saudi Arabia
April 19 – 20, 2017

- Australia
  - Zeyad Alwahabi* – U. Adelaide
  - Gus Nathan* - U. Adelaide
  - Jin-Soo Kim* – CSIRO
- Austria
  - Markus Haider* – TU Wien
- China
  - Fengwu Bai – Chinese Academy of Sciences
  - Zhiying Cui – Chinese Academy of Sciences
- France
  - Gilles Flamant – PROMES CNRS
- Germany
  - Reiner Buck – DLR
  - Miriam Ebert – DLR
- Italy
  - Roberto Solimene – IRC-CNR
- Spain
  - Jose Gonzalez – IMDEA Energy Institute
- Saudi Arabia
  - Hany Al-Ansary, King Saud University
- Turkey
  - Serdar Hicdurmaz – Middle East Technical University
  - Evan Johnson – Middle East Technical University
- UAE
  - Nicolas Calvet – Masdar Institute
- USA
  - Said Abdel-Khalik – Georgia Institute of Technology
  - Sheldon Jeter – Georgia Institute of Technology
  - Zhiwen Ma* – National Renewable Energy Laboratory
  - Ivan Ermanoski – Sandia National Laboratories
  - Cliff Ho – Sandia National Laboratories

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

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The presentation will summarise the research being undertaken at the University of Adelaide to advance understanding of heat transfer in particle-laden flows under conditions of relevance to solar particle receivers, together with that being undertaken to develop novel directly-irradiated solar particle receivers for applications in both solar power and chemistry. Detailed, in-situ and well-resolved measurements have already been performed using laser-diagnostic methods of the distributions of single-phase velocity, particle velocity and particle number density in a well characterized pipe-jet in the two-way coupling regime for a wide range of systematically varied Stokes numbers in a uniform co-flow. Detailed measurements of inflow conditions are also available to provide an environment that is well suited to the development and validation of numerical models. Measurements of simultaneous transport and carrier phase velocity are about to begin using a method to discriminate between the two phases based on particle size that has been under development for several years. A method to directly measure the temperature of individual particles in suspension using Laser-Induced Thermo-Phosphoresis heated directly with a 3 kW solid-state radiative heat source is also under development. Reliable temperature measurement has recently been demonstrated, which enables present work to be directed to extend the method to planar imaging and enable provide good spatial and temporal resolution.

Another program is advancing the understanding and development of both the transport characteristics and performance of a novel solar vortex receiver/reactor. A parallel experimental and numerical investigation has been undertaken to develop a novel configuration of directly irradiated vortex reactor that greatly mitigates particle deposition onto a window. Flow-field measurements have been performed with PIV, while direct measurements of particle deposition have also been performed to develop validated CFD models and devise improved configurations. Measurements of the performance of the reactor for application in solar gasification have also been performed in collaboration with ASTRI partners, while those to demonstrate alumina calcination have been performed in collaboration with ETH Zurich.

Design considerations for free falling particle receivers and experimental set-up for 5 m falling test.

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Basic design parameters for free falling particle receivers such as capacity and geometry of the receiver, size and properties of particle and flow rate and velocity of falling particles were related to give the particle volume fraction and solar energy absorption. High-level heat loss estimation was carried out to investigate the performance characteristics of falling particle receivers. For further investigations on the falling particle hydrodynamics and for identifying favourable design of large scale particle receivers, an experimental set-up with 5 m falling height has been prepared. A detailed design and camera-based characterization method will be presented.

Experimental Study of a Quartz Tube Solid Particle Air Receiver

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The quartz tube solid particle air receiver is a new type of solar receiver in which fluidized particles absorb the solar radiation directly and heat the air effectively, improving the efficiency of solar thermal power generation and reducing costs. Besides, the solid particle air receiver can overcome hot spot problem that is caused by non-uniform solar radiation on the receiver wall. In this paper, the experiment of single quartz tube solid particle air receiver is conducted on solar furnace system, which is intended to understand the influence of area receiving concentrated solar radiation.

The experimental results show that when the area that receives concentrated solar radiation becomes less, the average outlet air temperature decreases and the thermal efficiency of receiver increases. Small size solid particle can improve outlet air temperature that the highest outlet air temperature is 866.6ºC. The thermal efficiency of receiver can be up to 77.7% with less area receiving concentrated solar radiation. Transparent quartz glass tube, through which solid particles absorb concentrated solar radiation effectively, can benefit the thermal performance of receiver. Compared with receiver utilizing opaque glass tube, the single quartz tube solid particle air receiver performs better and is more suitable for concentrated solar power generation.

The particle-in-tube concept for concentrated solar energy conversion at high temperature

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In the particle-in-tube concept, a dense suspension of particles (small diameter -about 50-60 µm- group A of the Geldart classification) is created as an upward moving bubbling fluidized bed composed of about 30-40% of particles and 70-60% of air in volume. It moves upward vertically in the tubes constituting the solar absorber by the pressure difference imposed between the particle suspension dispenser and the tube outlet. Therefore the pressure difference creates a dense up-flow of particles at low air velocity (of the order of cm/s). This principle is completely different from the circulation of particles in a draft tube or in circulating fluidized beds where the gas velocity is of the order of 10 m/s (pneumatic conveying) and the particle volume fraction less than 5%.

The validity of this concept was proved at laboratory scale level (TRL 4) during the *CSP2* EU project (*Concentrated Solar Power in Particles*, N° 282932, 2011-2015). A 150 kW_{th} multi-tube solar receiver was successfully tested. The next step is currently under development in the framework of the *Next-CSP* H2020 EU project (*High temperature concentrated solar thermal power plant with particle receiver and direct thermal storage*, N°727762, 2016-2020). The Next-CSP project will demonstrate at industrial pilot scale (TRL5) the validity of the particle-in-tube concept atop the *Themis* facility solar tower. A 4-MW_{th} tubular solar receiver able to heat particles up to 800°C will be constructed and tested as well as the rest of the loop: two-tank particle heat storage and a particle-to-pressurized air heat exchanger coupled to a 1.2 MW_{el} gas turbine.

The presentation will summarize the results obtained up to now and the next steps including the challenges for the solar receiver and the particle heat exchanger.

FLUIDIZED BEDS FOR CONCENTRATED SOLAR POWER WITH THERMAL/THERMOCHEMICAL ENERGY STORAGE

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The exploitation of fluidized beds for Concentrated Solar Power (CSP) applications with thermal and/or thermochemical energy storage is gaining renewed interest. Fluidized solids may represent a promising alternative to other storage/exchange media entailing the possibility to avoid the use of “unfriendly” fluids and to operate the solar receiver at much higher temperature. These conditions would enable higher energy efficiency and/or coupling with high-temperature thermochemical cycles for solar energy storage. Dense gas fluidized beds for stationary combined and heat and power (CHP) generation may be optimized so as to accomplish three different and complementary tasks: 1) effective collection of densely concentrated solar radiation, 2) enhanced transfer of the incident power across the bed and to immersed surfaces, 3) effective storage/equalization of the inherently time-dependent radiative incident power for more efficient stationary power generation.

A novel concept of indirectly irradiated solar receiver for CHP generation consisting of a compartmented dense gas fluidized bed has been proposed and a pilot scale and a demonstration unit based on this concept have been constructed in Sicily, in the south part of Italy. The positive impact of fluidized bed compartmentation on the collection efficiency of the receiver and on the thermal properties of the fluidized bed has been investigated with the aid of computational fluid dynamical modelling and of experimental campaigns on purposely designed test rigs.

The option of directly irradiated fluidized beds was also scrutinized both for developing a new generation of solar particle receivers operated at higher temperature and for application to thermochemical energy storage. To this end, the role of the interaction of concentrated radiative fluxes with the fluidized particles moving under the action of bubble bursting was assessed with a focus on both the collection efficiency of CHP generation units and of the severity of thermal histories of bed solids, and closely associated solid-state transformations like sintering. The carbonation/calcination thermochemical cycle of calcium-based sorbents has been assumed as a reference case.

Integration of particle-based systems in central receiver solar power plants

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Particles-based Thermal Storage Systems (P-TES) avoid common problems such as freezing or degradation and increase operative temperature limits what allows their coupling with very efficient power cycles (supercritical cycles or combined cycles) or the use of new working fluids (sCO_2 or air), while providing non-expensive and massive storage solution for commercial plants, in central receiver solar power plants.. Thus solar plant flexibility introduced by the use of particles-based storage lead to multiple coupling options, as it is illustrated on Figure 1.

This work will briefly describe various multiple coupling options and will present various analyses on P-TES coupling DSG solar receiver to steam Rankine power cycle and coupling solar air receiver to subcritical & supercritical steam Rankine cycles and sCO_2 Brayton cycle.

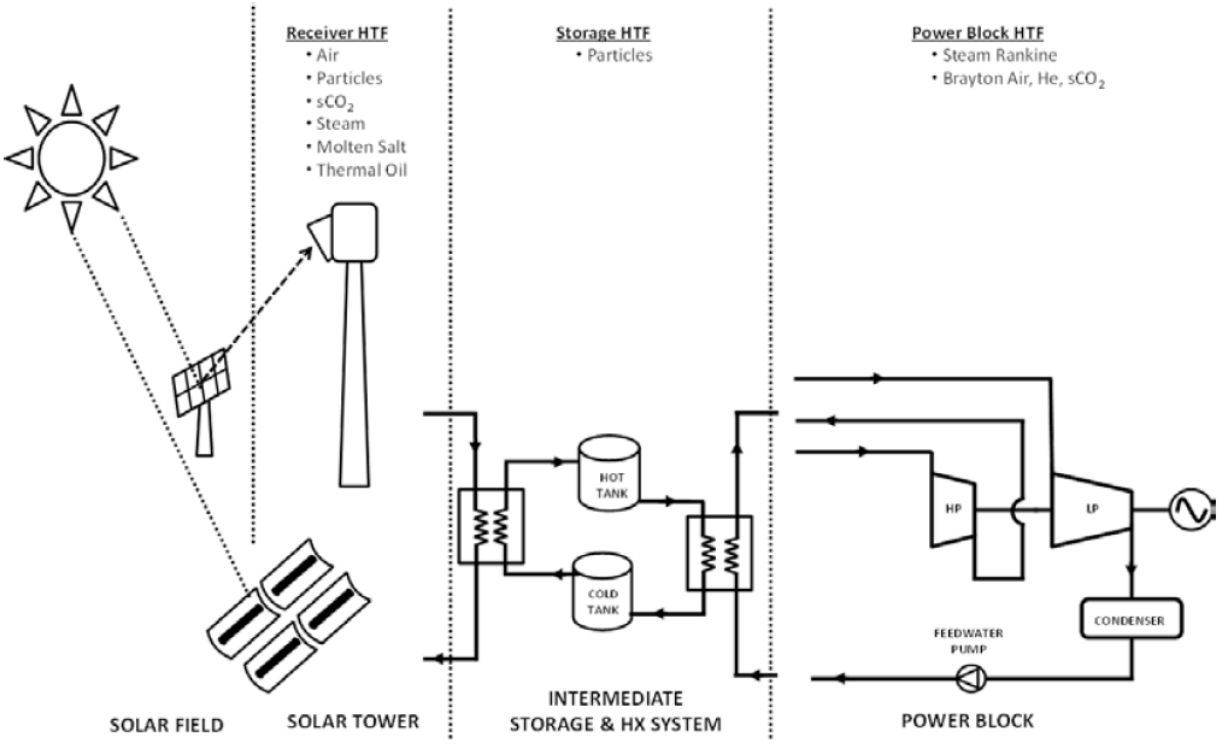

Figure 1. Intermediate energy storage concept using fluidized-bed technology

Development of Particle-Based Concentrating Solar Power System at NREL

Zhiwen Ma

Solid particles are attractive for a high-temperature concentrating solar power (CSP) system. Stable particles can be fluidized or in granular flow to exhibit fluid-like heat transfer characters. They have the ability to store large amount of thermal energy at a relatively low cost. Since 2011, NREL and its industry and academic partners have pursued solid particles as HTF for a low-cost, high-performance CSP system. Development of the particle thermal system includes particle receiver for solar energy collection, thermal energy storage, and heat exchanger for heating power cycle working fluid. This presentation will report the progress of particle CSP development at NREL. We have focused the development on solar receiver and periphery system including high-temperature particle storage. Solar receiver design is critical to the CSP system to collect and store energy for use in high-efficiency power cycles. NREL and its partners developed enclosed particle receiver design that aims at heating particles to temperatures of up to 800 °C with high thermal efficiency. The particle receiver uses solar-absorbing tubes or planar cavities formed by arrays of absorbers that create enclosed passages for particle flow and heat transfer. The cavity collectors improve solar flux collection, minimize optical reflection, and reduce thermal losses at high-temperature operation. The enclosed passages reduce direct heat and particle losses to the ambient. In addition to the receiver development, NREL's industry partner, Babcock & Wilcox (B&W) developed the auxiliary system and fluidized-bed heat exchangers to support and integrate with the particle thermal system. The presentation to the SolarPACES PTWG will show the component and system design approach.

Experimentation and Modeling of a Dense Granular Flow Receiver

and

CFD Modeling of a Fluidized Sand Bed for Thermal Energy Storage

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A solid particle receiver design is proposed which uses a gravity driven, dense granular flow instead of fluidized or falling particles. Through experimentation with sand, the flow and heat transfer properties were studied in two geometries: vertical tubular and vertical parallel plate. Experiments were run to determine the effective thermal conductivity of the flowing sand, which was then used to model a 5 by 5 meter, finned solar receiver in ANSYS Fluent. Several different fin configurations and radiation levels were studied, with key model outputs of thermal efficiency and maximum absorber temperature.

A thermal energy storage system was designed where heated sand particles are stored in an array of rectangular tubes measuring 0.28 m x 0.025 m x 1 m. When heat extraction is desired, the sand is fluidized with air, and heat is transferred from particles to the air while passing through the bed. Depending on instantaneous demand during the night, the heated air passes through as many sand beds as necessary to reach the design temperature of the power cycle. Modeling was performed with a closed air Brayton cycle, but an additional heat exchanger could be used if a different working fluid is desired. In this numerical study, both hydrodynamics and heat transfer of the fluidized sand bed were modelled with ANSYS Fluent.

Desert sand characterization for high-temperature particle solar receiver

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Desert dune sand is considered as a potential sensible heat thermal energy storage (TES) material. Several samples are collected from different locations of the desert of the United Arab Emirates, and their thermal and mechanical properties are measured. After an initial mass loss that occurs during the first heating cycle, the samples appear to be thermally stable from approximately 650 °C to 1000 °C. Higher temperatures lead to agglomeration issues. The optical properties are studied to consider the use of desert sand as well as a direct solar absorber. The transformation of calcium carbonate into calcium oxide during the first heating process has a negative impact on the solar-weighted absorptivity. It is therefore advised to research collection points with low carbonate content.

Particle receiver and system development at DLR: status and perspective

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The presentation will give an overview over particle technology work at DLR. Several receiver technologies for different applications will be described: falling particle, centrifugal, rotary kiln and moving film receiver.
For the falling particle receiver configuration, CFD simulations for a commercial-scale receiver, using a face-down configuration, are presented.
The centrifugal receiver uses a rotating cylindrical cavity where the particles are moving slowly along the wall. A 10kW prototype system was successfully tested up to 900°C. Test results are compared with simulation results. A 500kW demonstration unit was built, and some non-solar pretests were carried out. Flow characteristics of the particle film will be discussed. This receiver is currently being installed at the solar tower Jülich, begin of solar tests is planned for summer 2017. Potential applications of this demonstration system for process heat applications will be described.
The rotary kiln receiver is mainly intended for thermochemical applications like redox reactions or calcination. Tests with a lab-scale prototype are presented. Furthermore, an irradiated moving bed receiver for redox reactions is described.

Work on particle-based steam generators, with particles moving by gravity through a tube bundle, is outlined. Emphasis is on understanding flow characteristics in the moving bed and on the determination of heat transfer characteristics, both by experiments and simulation.

Thermal storage development is directed towards regenerator storage with different types of particles as inventory. Simulation and experimental testing are described.

Abrasion and attrition are important aspects for the durability of particle receivers and systems. Several test methods were applied to bauxite particles, indicating that attrition is within acceptable limits. However, first results for erosion of high-temperature alloys by moving particles show the need for detailed analysis. Other DLR test equipment and results will also be described.

High-temperature particle receivers and reactors for concentrating solar power and thermochemical fuel production

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This presentation summarizes research at Sandia National Laboratories to develop high-temperature particle receivers and reactors for concentrating solar power and thermochemical fuel production.

CSP: A 1 MW_t continuously recirculating falling particle receiver has been demonstrated at Sandia National Laboratories using commercial ceramic particles (CARBO Accucast ID-50, 280 μm nominal particle diameter). Free-fall and obstructed-flow receiver designs were modeled and tested with particle mass flow rates of ~1 – 7 kg/s and average irradiances up to 1,000 suns. Average particle outlet temperatures exceeded 700 °C for the free-fall tests and reached nearly 800 °C for the obstructed-flow tests, with peak particle temperatures exceeding 900 °C. High particle heating rates of ~50 to 200 °C per meter of illuminated drop length were achieved for the free-fall tests with mass flow rates ranging from 1 – 7 kg/s and for average irradiances up to ~ 700 kW/m^2. Higher temperatures were achieved at the lower particle mass flow rates due to less shading. The obstructed-flow design yielded particle heating rates over 300 °C per meter of illuminated drop length for mass flow rates of 1 – 3 kg/s for irradiances up to ~1,000 kW/m^2. The thermal efficiency was determined to be ~60 – 70% for the free-falling particle tests and up to ~80% for the obstructed-flow tests.

Thermochemical Fuels: The Cascading Pressure Reactor (CPR) is a development of an earlier particle-based reactor design—both of which aim to use metal oxide or other particles as the redox material for two-step thermochemical H_2O or CO_2 splitting. In addition to their redox role, particles in the CPR also serve as the medium that enables an over 1000-fold pressure ratio between the thermal reduction (TR) and the oxidation step of the two-step cycle. This pressure ratio is essential for achieving high cycle efficiencies. The reactor concept, its salient features, their implementation into the existing reactor prototype, and lessons learned from its design, construction, and testing will be discussed.

Discrete Structure Particle Heating Receiver and Related Concentrator Solar Power Research at the Georgia Institute of Technology

Faculty: Said Abdel-Khalik, Matt Golob, Clayton Nguyen, and Sheldon Jeter
Graduate Students: Kenzo Repole, Matt Sandlin, Ramy Imam, and Lucy Shen
Georgia Institute of Technology

Hany Al-Ansary and Abdelrahman Elleathy
King Saud University

The Thermal and Solar Energy group at Georgia Tech (GIT) is presently conducting or has recently completed several projects related to or supporting Discrete-Structure Particle Heating Receiver (DS-PHR) technology and related Concentrator Solar Power (CSP) and Concentrator Solar Chemistry (CSC) technologies. Most of these projects have been performed in collaboration and cooperation with researchers from King Saud University (KSU) and others have involved research in conjunction with Sandia National Laboratory. An important KSU-GIT project is the continuing support of the development of the 300 kW-th solar power tower test and demonstration facility at the Riyadh Techno-Valley (RTV) near the KSU campus. Supporting and related projects included studies of: (1) heat transfer between surfaces and both rapidly flowing particulate and moving packed particle beds; (2) durability of flowing particulates and exposed DS-PHR mesh materials at high temperature; (3) susceptibility of particulates to agglomeration or sintering at high temperature and pressure representative of thermal energy storage (TES) conditions; and (4) efficiency of DS-PHR designs tested at lab scale in the Georgia Tech High Flux Solar Simulator and at larger scale at the Sandia National Solar Thermal Test Facility (NSTTF). Other research and development has included work on the design, modeling, and optimization of particle lift systems, which has confirmed the feasibility and cost-effectiveness of the insulated skip hoist for PHR applications. We have also conducted considerable work on particle to fluid heat exchanger (PFHX) design and implementation including the preliminary modeling and optimization of various candidate PFHX designs for both sc-CO2 and moderate pressure gas turbine systems. More recently we have been working on the concentrator solar aspects of CSC systems including the preliminary design and modeling of secondary concentrator and beam-down systems for these applications.

Discrete Structure Particle Heating Receiver Technology and Related Concentrator Solar Power Developments at King Saud University in Collaboration with Georgia Tech

Hany Al-Ansary and Abdelrahman Elleathy
King Saud University

Said Abdel-Khalik and Sheldon Jeter
Georgia Institute of Technology

Several Discrete-Structure Particle Heating Receiver (DS-PHR) technology and related Concentrator Solar Power (CSP) developments are continuing successfully at King Saud University (KSU), some in collaboration with the Georgia institute of Technology. A key project has been the development of our nominally 300 kW-th solar power tower project at the Riyadh Techno-Valley (RTV) development near the KSU campus. The KSU-RTV facility was originally designed to be a flexible test facility with the capacity to be modified as needed in the future. Currently the facility is being repurposed as a fully integrated high-temperature solar gas turbine (HTSGT) demonstration. The needed modifications, especially the procurement and integration of a suitable 100 kW-electrical gas turbine and an appropriate high temperature particle to working fluid heat exchanger, have been identified, engineered, and implemented in a fast track process. Of special note is the design and implementation of the new support structure for the gas turbine and its auxiliaries which minimizes the high temperature and moderate pressure piping required. Other structural, mechanical, piping, and electrical auxiliaries and sub-systems and new instrumentation and control components have been selected, engineered, and implemented. The facility should be coming on line just prior to the meeting of the Particle Technology Working Group in Riyadh. Other notable research and development at KSU and the RTV facility includes work on cost effective thermal energy storage (TES) designs and materials as well as investigation of especially low cost particulates.

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

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Univ.Prof.Dr.Markus Haider, Institute for Energy Systems and Thermodynamics, TU Wien, Austria

The Institute of Thermal Energy Systems at TU Wien in Austria has been working since 2011 on the development of a particle based TES system. We are concentrating our research efforts on system design, system modelling, and on the development of an advanced pure counter current fluidized bed heat exchanger with minimum solids inventory and minimized auxiliary power.

The research group is operating two hot test rigs and three cold test installations. The largest test rig has a thermal capacity of 200-280kWth and 1MWh of Energy, and a maximum operating temperature of 390°C (due to using thermal oil). The current research effort is aiming at fully validating the operational behaviour, the performance data and the scale up factors. Current particle material is 80µm sand.
A next generation design is under development but cannot be disclosed yet (patent pending). Beside experimental development, the research group has published several papers dealing with the optimum design of particle based CSP systems, of the design of ACAES systems and the application of particle based test in the flexibilisation of thermal power plants.