2017 Project Abstract
For the Period Ending June 30, 2021

PROJECT TITLE: Extraction of Solar Thermal Energy in Minnesota
PROJECT MANAGER: Lian Shen
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FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2017, Chp. 96, Sec. 2, Subd. 07a as extended by M.L. 2020, First Special Session, Chp. 4, Sec. 2

APPROPRIATION AMOUNT: $250,000
AMOUNT SPENT: $250,000
AMOUNT REMAINING: $0

Sound bite of Project Outcomes and Results

We developed a novel solar particle receiver technology for absorbing, storing, and utilizing solar thermal energy. Extensive experiments utilizing innovative imaging techniques on laboratory apparatuses, assisted by state-of-the-art simulations on supercomputers, have been conducted. Valuable data have been collected for solar energy applications specifically for the sun conditions in Minnesota.

Overall Project Outcome and Results

The objective of this project is to develop a novel solar particle receiver technology as a low-cost, high-efficiency way to absorb, store, and utilize solar thermal energy. Traditional concentrated solar thermal systems use mirrors to concentrate solar radiation. However, at Minnesota's latitudes the sun radiation is not sufficiently strong to achieve this goal with the standard type of solar thermal systems. Almost all solar energy installations in the state are photovoltaic (PV), but the PV systems require sophisticated materials for energy conversion and energy storage is more difficult than solar thermal systems.

In this project, we have conducted extensive experiments to study how to design, build, and test a prototype of solar particle receiver. Leveraging on laboratory apparatus that our team built, we measured the motions of solid particles in a duct to obtain valuable experiment data using advanced laser illumination and high-speed camera imaging technologies. A specialized solar particle solar receiver was constructed and calibrated, in which we have developed a three-dimensional riser with a controllable airflow and particle mass flow rate. We have also developed a predictive tool for the computation of the interactions between solar particles and air flows, which provided valuable data to reveal the flow physics and reduced the design cycle of solar particle receiver. Utilizing the above research approaches, we have performed extensive tests on the solar particle receiver prototype under various conditions that replicate the high temperatures, gas atmosphere, and heating rates involved in a concentrated solar facility. A laboratory scale solar receiver has been developed to study heat transfer in concentrating solar power systems. The research results obtained in this project greatly facilitate a meaningful transition from laboratory experiments to operations under concentrated solar radiation for solar energy applications particularly suitable for Minnesota's environment.

Project Results Use and Dissemination

In this project, substantial efforts have been put into sharing the knowledge gained from the research. The research results were shared with the specialists in concentrated solar power generation at the National Renewable Energy Laboratory of the Department of Energy. The findings of this project were presented at the national conference of the American Physical Society for multiple years. A paper has been published in the

Journal of Fluid Mechanics (“Velocity and spatial distribution of inertial particles in a turbulent channel flow” by Fong, Amili and Coletti, vol. 872, pp.367-406), which is a leading journal in the field.

Environment and Natural Resources Trust Fund (ENRTF) M.L. 2017 LCCMR Work Plan Final Report

Date of Status Update: August 15, 2021

Final Report

Date of Work Plan Approval: 06/07/2017

Project Completion Date: June 30, 2021

PROJECT TITLE: Extraction of Solar Thermal Energy in Minnesota

Project Manager: Lian Shen

Organization: University of Minnesota, St. Anthony Falls Laboratory

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Location: Statewide

Total ENRTF Project Budget:

ENRTF Appropriation:	**$250,000**
Amount Spent:	**$ 250,000**
Balance:	**$0**

Legal Citation: M.L. 2017, Chp. 96, Sec. 2, Subd. 07a as extended by M.L. 2020, First Special Session, Chp. 4, Sec. 2

Appropriation Language:
$250,000 the first year is from the trust fund to the Board of Regents of the University of Minnesota to develop new solar particle receivers as a low-cost, high-efficiency, and clean technology to absorb, store, and utilize solar thermal energy. This appropriation is subject to Minnesota Statutes, section 116P.10. This appropriation is available until June 30, 2020, by which time the project must be completed and final products delivered.

M.L. 2020 - Sec. 2. ENVIRONMENT AND NATURAL RESOURCES TRUST FUND; EXTENSIONS. [to June 30, 2021]

I. PROJECT TITLE: Extraction of Solar Thermal Energy in Minnesota

II. PROJECT STATEMENT:

The objective of this project is to develop a novel Solar Particle Receiver (SPR), a low-cost, high-efficiency technology to absorb, store, and utilize solar thermal energy.

The most prevalent concentrated solar thermal systems use mirrors to concentrate solar radiation on the surface of a pipe, which then transfers heat to a fluid running in it. For the hot fluid to produce electricity (for example to power a turbine generator), its temperature needs to be at least 500°C (almost 1000°F). At Minnesota's latitudes the sun radiation is not sufficiently strong to achieve this goal with the standard type of solar thermal systems. In fact, almost all solar energy installations in the state are photovoltaic (PV), which convert radiation directly into electricity. However PV systems require sophisticated materials for energy conversion. Also, because electricity is difficult to store, PV solar systems are only usable when the sun is shining.

The SPR technology represents a step change in solar thermal energy. In these systems particles suspended within the fluid (typically a gas) directly absorb the sunlight and transfer the heat evenly throughout the fluid. This means higher energy absorption and heat transfer rates, higher efficiency of the system, and much less solar radiation needed to reach the required fluid temperatures. Importantly, the hot particles also serve as a chemically benign, low-cost heat storage medium, which is crucial to utilize the solar energy around the clock: energy can be stored during daytime and used to extend power generation during cloudy days or at night. Heat storage is much cheaper than storing electric energy in large batteries: even for a relatively small 10 MW power plant, to store the daily absorbed energy one would need a 400 ton battery, which at the present market price would cost about 30 million dollars.

The concept of SPR has been demonstrated in pilot sites, using curtains of free falling particles and slow gas-particle streams. Most of these installations use large particles, essentially pebbles, in the centimeter range. These pebbles are not very good at releasing heat to the air through which they fall. This problem is due to the fact that large particles have a limited surface area per unit volume, and they fall too fast to have sufficient time to release the heat to the fluid. In these conditions the process is not very efficient: at most 20% of the incoming solar energy is available to generate electricity, and energy extraction becomes advantageous only with a level of solar radiation typical of Southwest US. On the other hand, the new concept of solar receiver we propose uses fine particles, which greatly alleviates the limitations mentioned above. Specifically, we will use silica particles of just 20 microns in size. These particles are extremely cheap and have been shown to be excellent absorbers of sunlight. Some exploratory study of this approach has been carried out, but only at small scales. For this technology to move from laboratory experimentation to the energy market, the SPR performance needs to be tested in realistic situations, including high gas flow rates and exposed to radiation like that in a solar field.

We therefore propose to design, build, test, and optimize an SPR prototype, to demonstrate its viability for the Minnesota energy needs. Our target is to reach temperatures of 1000°F in the dusty air, and with a heat transfer efficiency of 35%. In order to achieve this, we will determine the optimal set of design parameters that maximizes thermal efficiency in realistic operating conditions. For this purpose we will leverage existing facilities and resources available to our team, including: (i) a flow facility in which air flow laden with microscopic particles is metered and analyzed; (ii) a solar simulator facility that reproduces concentrated solar radiation in the laboratory; (iii) a performance prediction tool that uses the power of super-computing. Finally we will use our results to assess the economical and environmental benefits of implementing this novel and optimized SPR design in large-scale solar thermal fields.

III. OVERALL PROJECT STATUS UPDATES:

Project Status as of July 1, 2018:

We have carried out initial tests of unheated particle-laden duct flow in the existing facility, highlighting the important regimes and physical mechanisms for particle transport and accumulation. We determined the need to design two new versions of the model for unheated and heated tests. Both these models are being designed and built. We expanded our computational tools to include heat transfer in the particle-laden flow simulations, and we are developing the capability of simulating radiative transfer. A first manuscript on the unheated particle-laden flow test is in preparation for publication.

Project Status as of November 7, 2019:
We have performed experiments observations on the velocity response and topological distribution of highly concentrated, falling inertial particles in the vertical rectangular duct without heat transfer. We are comparing the experimental results in the non-heated particle-laden gas duct to the newly developed computer model. Parameters under evaluation include the domain size and particle properties. A laboratory scale solar receiver was developed to study heat transfer in concentrating solar power (CSP) systems in which solid ceramic particles are heated to provide thermal energy storage. The results are being analyzed.

Project Status as of May 27, 2020:
The imaging experiments on the particle-laden duct facility have allowed us to identify a critical threshold for the formation of particle clusters, which are expected to impair the transmission and absorption of solar radiation through the particle-laden flow. The computational toolbox was expanded to include particle-resolved simulations. A laboratory scale solar receiver was developed to study heat transfer in concentrating solar power (CSP) systems in which solid ceramic particles are heated to provide thermal energy storage (TES). Experiments were conducted in the University of Minnesota solar simulator at commercially relevant temperature and solar concentration.

Project extended to June 30, 2021 by LCCMR 6/18/20 as a result of M.L. 2020, First Special Session, Chp. 4, Sec. 2, legislative extension criteria being met.

Project Status as of Sept 18, 2020:
We completed the design and initiated the construction of the particle-laden duct flow with heated walls, which will allow to evaluate the change in convective heat transfer coefficient due to the presence of particles suspended in the gas flow. A direct comparison between particle-resolved simulations and experiments in underway for the non-heated cases at various volume fractions (up to 1%). The laboratory scale solar receiver, developed to study heat transfer in concentrating solar power (CSP) systems, was tested at commercially relevant temperature and solar concentration. For particle volume fractions of order 10^-3, heat transfer coefficients are of order 80 W/(m^2*K).

Amendment Request as of October 12, 2020

PI Filippo Coletti has moved to ETH Zurich, Switzerland. While he will continue being involved on the two projects he has with LCCMR (he still supervises personnel working on them in Minnesota), he will not be the principal investigator anymore. This role passes to Prof. Lian Shen, who is the director of Saint Anthony Falls Laboratory and has been a co-investigator in both projects from the start.

Approved by LCCMR 12/6/20

Project Status as of March 4, 2021:
There were no new experiments performed since the last update because the University of Minnesota has reduced operations in laboratories due to the pandemic. Our research efforts were on analyzing the data collected before COVID-19 and performing computer simulation studies. We have discovered particle clustering properties and connected them to turbulence eddy size and dissipation rate. Our research findings are valuable for the improvement of Solar Particle Receiver for solar energy extraction.

Amendment Request as of March 4, 2021

Because of COVID-19, the University of Minnesota has reduced operations in laboratories. As a result, there were no experiments performed in the past period and it is unlikely that the laboratories will be back to normal before the project completion date of June 30, 2021. Meanwhile, we had already collected substantial amount of experiment data before the pandemic for the research, and there is a need to continue the data analysis in the remaining period of the project. Therefore, we request the rebudget the remaining $157 in the "Lab Supplies" category and the remaining $5,765 in the "Other" category for machining of prototype components to the "Personnel (Wages and Benefits)" category.

Amendment Approved by LCCMR 4/30/21

Overall Project Outcomes and Results:
The objective of this project is to develop a novel solar particle receiver technology as a low-cost, high-efficiency way to absorb, store, and utilize solar thermal energy. The most prevalent concentrated solar thermal systems use mirrors to concentrate solar radiation. However, at Minnesota's latitudes the sun radiation is not sufficiently strong to achieve this goal with the standard type of solar thermal systems. Almost all solar energy installations in the state are photovoltaic (PV), but the PV systems require sophisticated materials for energy conversion and energy storage is more difficult than solar thermal systems.

In this project, we have conducted extensive experiments to study how to design, build, and test a prototype of solar particle receiver. Leveraging on laboratory apparatus that our team built, we measured the motions of solid particles in a duct to obtain valuable experiment data using advanced laser illumination and high-speed camera imaging technologies. A specialized solar particle solar receiver was constructed and calibrated, in which we have developed a three-dimensional riser with a controllable airflow and particle mass flow rate. We have also developed a predictive tool for the computation of the interactions between solar particles and air flows, which provided valuable data to reveal the flow physics and reduced the design cycle of solar particle receiver. Utilizing the above research approaches, we have performed extensive tests on the solar particle receiver prototype under various conditions that replicate the high temperatures, gas atmosphere, and heating rates involved in a concentrated solar facility. A laboratory scale solar receiver has been developed to study heat transfer in concentrating solar power systems. The research results obtained in this project greatly facilitate a meaningful transition from laboratory experiments to operations under concentrated solar radiation for solar energy applications particularly suitable for Minnesota's environment.

IV. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1: Build, design, and test a prototype of Solar Particle Receiver
Description: In this activity we will leverage an existing laboratory apparatus that our team built to investigate the flow of gas-particle mixtures. This consists of a 2.5 meter tall duct in which air flows at up to 300 liters/min, carrying microscopic solid particles injected at precise concentrations. We will use silica carbide particles, a low-cost material that absorbs 80% of the incoming thermal radiation, and will irradiate them using our solar simulator: an array of seven 6.5 kW xenon lamps that produces a radiation flux up to 8.5 MW/m^2. This facility is the most powerful of its kind in the country, and produces concentrated radiation equivalent to that given by parabolic mirrors over 500 acres of land and focused over a 3 square inch spot. The radiation will be transmitted through a transparent quartz window on the channel, so that the dusty air can be heated. We will vary the design parameters (air flow rate, particle size and concentration) and monitor the device performance in terms of thermal efficiency. To this end we will use a calorimeter, a device that measures the amount of radiation transmitted through the air-particle mixture, and so indirectly measures the radiation absorbed by the particles. We will also measure the air flow temperature using thermocouples.

ENRTF Budget	**$92,357**

Outcome	Completion Date
1. Design and build a prototype of Solar Particle Receiver	January 2019
2. Measure thermal efficiency of the receiver in different air-particle mixture regimes.	January 2021

Activity 1 Status as of July 1, 2018:
We have carried out extensive measurement of the transport of solid particles in the unheated duct. We used laser illumination and high-speed camera imaging to characterize the motion of the particles carried by the downward air flow. This has allowed identifying different flow regimes and demonstrated a tendency of the particles to sample specific regions of the flow. In particular, the particles were shown to concentrate close to the duct walls, which poses challenges for the direct illumination of the particles through a transparent window. Moreover, we carried out an analysis of the needed amount of particles to absorb the desired amount of radiation, taking into account the properties of available particles suitable for concentrated solar power applications. We obtained substantial amounts of ceramic-based particles and characterized their size distributions. We also tested their compatibility with the particle-feeding system and determined the achievable mass flow rate. Based on these results, we elected to design two separate particle-laden duct models: one unheated and with full optical access, to characterize the particle-flow interaction and the viability of different regimes; and one to be radiated by the University of Minnesota solar simulator, which needs to withstand the high radiative fluxes and be instrumented with temperature sensors and a calorimeter. We are now in the process of designing and building both models, which will operate under the same regime of air and particle transport.

Activity 1 Status as of January 1, 2019:
We used the unheated model to investigate how particles flow and cluster under different air flow speeds and solid volume fractions. We built a regime map that allows us to vary the residence time of the particles in the duct. A specialized solar particle solar receiver was completed, calibrated and is ready for evaluation in the Department of Mechanical Engineering's indoor concentrated solar simulator. This facility is a prototype of a solar receiver for storage of solar energy in particle flows, thus providing thermal storage for electricity production. Granular media comprising an ensemble of solid particles made of ceramic/refractory materials are leading contenders for heat-storage for high temperature concentrated solar power (CSP) technologies to interface with high-efficiency power cycles, including the supercritical carbon dioxide (sCO2) cycle. The goal is to relate heat transfer behavior to the underlying morphology (particle size, shape factor, and solid volume fraction) and flow regimes of granular media. This study will lead to determination of how to select granular media for optimal heat-transfer performance of particle-based solar receivers. The specialized receiver has been instrumented to control the mass and flow rate of particles and to measure the transient heat transfer to the particles as a function of volume fraction, particle size, particle morphology and material. The particle delivery system and the solar simulator have been calibrated and a real time data collection and control program has been developed. Experiments with 250 micrometer Accucast-ID (high-alumina ceramic) particles will commence in April 2019.

Activity 1 Status as of November 7, 2019:
We have performed experiments on the velocity response and topological distribution of highly concentrated, falling inertial particles in the vertical rectangular duct without heat transfer. The working fluid is air laden with size-selected glass particles. The experiment is conducted in two different configurations of free-falling particles, and particles suspended by flowing air, enabling particle volume fractions as high as 3E-2. Two different resolutions are employed: a full-scale view to capture large-scale motions of the particles and cluster formation using particle image velocimetry; and a zoomed-in view to resolve the individual motions of particles using particle tracking velocimetry. We characterized the influence of clusters on the mean statistics, and the partitioning of particle velocities into spatially correlated and random uncorrelated motions. These factors are important in view of heat transfer properties, to be tested next.

Activity 1 Status as of May 27, 2020:

We have developed a 3-dimenisonal riser with a controllable airflow and particle mass flow rate, allowing for a consistent particle volume fraction inside the riser. While the imaging results are two-dimensional, the experimental setup allows 3-dimensional phenomena including the formation of clusters to occur. By varying the airflow and the particle feed rate, we have obtained results for the gas-solid riser in a volume fraction range from 3×10-4 to 8×10-3. Increasing the airflow results in a greater particle volume fraction due to the suspensions of particles by the upwards airflow. In several of these cases, a clustering of particles is observed as well. It was possible to identify a threshold concentration beyond which particle clustering occurs. This is important because it will impair the transmission of solar radiation through the system.

Activity 1 Status as of September 18, 2020:
We continue analyzing the data of the non-heated particle-laden duct experiment. We found that the concentration threshold for the initiation of particle clustering (about 0.5% in volume fraction) is independent of the airflow rate. This is important, as it allows us to extend our considerations beyond this prototype and towards large-scale receivers. We also discovered that, above such concentration threshold, particles cluster even when the fall freely in the duct, without an upward air flow. We completed the design and initiated the construction of the particle-laden duct flow with heated walls, which will allow to evaluate the change in convective heat transfer coefficient due to the presence of particles suspended in the gas flow. The experiment requires maintaining the heated wall temperature constant, which in turn led to the design of a PID control system and a thermal guard to reduce conduction losses.

Activity 1 Status as of March 4, 2021:
Because of COVID-19, the University of Minnesota has reduced operations in laboratories. As a result, there were no more experiments performed in the past period. Nevertheless, there were substantially data collected before the pandemic. We continued to analyze the experiment data with a focus on the particle clustering properties. We developed a novel methodology to track clusters across successive instances of the flow. Through analyses, we elucidated several key features of the clusters. It is found that the cluster lives have typical durations of a few Kolmogorov time scales, and their lifetimes are strongly related to their size such that large clusters tend to be long-lived. Clusters formed by particles with more inertia last longer in time, and gravitational settling also increases lifetime.

Final Report Summary:
We have performed extensive experiments to study how to design, build, and test a prototype of solar particle receiver. Leveraging on laboratory apparatus that our team built, we measured the motion of solid particles in a duct under unheated and heated conditions to obtain valuable experiment data. We used laser illumination and high-speed camera imaging to characterize the velocity of the particles carried by the air flow in the duct. We investigated how particles flow and cluster under different air flow speeds and solid volume fractions. A specialized solar particle solar receiver was constructed and calibrated. We have also developed a three-dimensional riser with a controllable airflow and particle mass flow rate.

ACTIVITY 2: Optimize the performance of the Solar Particle Receiver
Description: In this activity we will incorporate the findings of Activity #1 into an advanced predictive tool to calculate the SPR thermal efficiency. We will leverage a state-of-the-art framework that our team has developed and used extensively to simulate flows of fluid and particles in environmental and renewable energy settings. Our model incorporates the laws of physics involved in the energy transfer processes, which are expressed as mathematical equations and solved by a cluster of 17,000 computers working in parallel. To this end, the existing framework will be extended to include thermal radiation. The results will be validated against the laboratory experiments. We will then exploit the super-computer capabilities available at St. Anthony Falls Laboratory to evaluate the performance of numerous sets of design parameters, which would take an excessive amount of time to be tested experimentally. This will greatly speed up the design cycle, allowing us to virtually test and compare tens of combinations of parameters. Specifically, in the simulations we will vary: flow rate, particle concentration,

particle size, radiation intensity, and cross-sectional channel dimension. An especially important aspect on which the simulations will shed light is the phenomenon of particle accumulation near the walls. This phenomenon, which is especially strong when the flow rate becomes turbulent, is expected to strongly influence the performance of the solar particle receiver.

ENRTF Budget	**$69,413**

Outcome	**Completion Date**
1. Extend the existing predictive tool to include thermal radiation	January 2019
2. Validate the model against laboratory results	January 2019
3. Vary systematically the simulation parameters until the optimal efficiency is obtained	June 2021

Activity 2 Status as of July 1, 2018:
We have extended our computational toolbox to include the effect of heat transfer to and from the wall and through the particle-laden gas flow. The tool capabilities have been validated with experimental data in the literature. We also characterized the ability of the tool to be utilized with large super-computing facilities, such as those available at the University of Minnesota. We are now incorporating the feature of thermal radiation through the particle-laden gas flow.

Activity 2 Status as of January 1, 2019:
We have made major improvements to our computational toolbox to achieve much higher simulation speed, which will be critically helpful for reducing the design cycle in the project. Another great advantage of the new computational capability is that it can simulate substantially more particles than the previous methods. Moreover, unique properties can now be assigned to each individual particle, and it is flexible to add new features to our toolbox. Preliminary validation on the new computational toolbox has been done. Literature review on thermal radiation has also been done. We are now validating the temperature field on the new toolbox, and radiation effects will be considered subsequently.

Activity 2 Status as of November 7, 2019:
We are presently comparing the experimental results in the non-heated particle-laden gas duct to the newly developed computer model. Parameters under evaluation include the domain size and particle properties. The computer model is sensitive to restitution coefficient and friction coefficient of the particles, therefore these will have to be determined experimentally in order to reach a meaningful comparison.

Activity 2 Status as of May 27, 2020:
We have developed a numerical approach to simulate the dynamics of particles that resolves the scales of the particles themselves (particle-resolved simulations). While this is not applicable to the full-scale reactor, the high accuracy of this approach can be leveraged to obtain meaningful comparisons with experiments in domains of limited size, and to obtain unknown terms in the equations governing the coarse-grained transport.

Activity 2 Status as of Sept 18, 2020:
A direct comparison between particle-resolved simulations and experiments in underway for the non-heated cases at various volume fractions (up to 1%). One of the main challenges we are tackling include the wall-particle collisions, which require directly validated restitution coefficients and friction coefficient (static and dynamic), for the particle and wall materials at hand. Another challenge is the vertical extension of the duct, which in our case is made periodic in the streamwise direction. We are evaluating the realism of this assumption, by measuring the correlation length of the particle motion, both in terms of particle velocity and particle concentration. We are also incorporating models for the thermal transport in the gas-particle mixture, in view of direct comparisons with the

heated-wall experiments. For that, we are evaluating different approaches to modeling the particles (lump body versus variable temperature).

Activity 2 Status as of March 4, 2021:
Because of COVID-19, the University of Minnesota has reduced operations in laboratories. As a result, there were no experiments performed in the past period. Besides analyzing the experiment data obtained prior to the pandemic, substantial efforts have been put on the computer simulation based research. We further improved our computational method for it to have the capability to accurately simulate the particle-particle interactions and particle-wall interactions. We also analyzed the simulation results for the particle clustering behavior in the bulk flow, and connected the particle clustering to the energy dissipation in the turbulent flow.

Final Report Summary:
We have developed a predictive tool for the computation of the interactions between solar particles and air flows. Our computational framework captures the effect of heat transfer to and from the wall and through the particle-laden gas flow. The tool capabilities have been validated with experimental data. A great advantage of our new computational capability is that it can simulate substantially more particles than the previous methods. It can also resolve the scales of the particles themselves (i.e., particle-resolved simulations). The simulation tool is useful for providing valuable data to reveal the flow physics and reducing the design cycle of solar particle receiver.

ACTIVITY 3: Demonstrate the optimized design of Solar Particle Receiver and evaluate benefits
Description: In this activity we will perform new tests on the SPR prototype under conditions that replicate the high temperatures, gas atmosphere, and heating rates involved in a concentrated solar facility using the University of Minnesota's 45 kW indoor high-flux solar simulator. This activity will achieve a meaningful transition from laboratory experiments to operation under concentrated solar radiation. We will compare the data with the predicted performance, using the optimal set of parameters (flow rate, particle concentration, etc.) indicated by the simulations carried out in Activity #2. Modifications to the prototype may be applied to improve performance. We will then verify the predicted improvement in thermal efficiency in the solar simulator. The experimental validation of the computer model will be crucial, as it will demonstrate that the model can be used as an accurate prediction tool for future designs of devices at larger scale. Using information on solar irradiation, cost of fossil fuel, and efficiencies of existing power plants (which is available from sources such as the National Renewable Energy Laboratory), we will implement a software to quantify the positive impact of the new SPR design in terms of energy saving and reduction of pollution.

ENRTF Budget	**$88,230**

Outcome	**Completion Date**
1. Carry out performance measurements at predicted optimal regimes	January 2020
2. Demonstrate competitive thermal performance at radiation levels typical of Minnesota	June 2020
3. Quantitatively assess environmental benefit of optimized solar receiver design	June 2021

Activity 3 Status as of July 1, 2018:

Activity 3 Status as of January 1, 2019:
Design and manufacturing of the components needed for the radiative testing phase have been initiated.

Activity 3 Status as of November 7, 2019:

A laboratory scale solar receiver was developed to study heat transfer in concentrating solar power (CSP) systems in which solid ceramic particles are heated to provide thermal energy storage (TES). The 4 kW laboratory solar receiver is intended for evaluation of the impacts of particle material and size, particle flow rate and volume fraction on heat transfer to particles flowing through a vertical tube under gravitational acceleration. Gravity-flow of particles reduces the energy requirements of the system and system complexity compared to fluidized beds and rotating receivers. Experiments were conducted in the University of Minnesota solar simulator at commercially relevant temperature and solar concentration. We used commercially available 280 micron ceramic particles and solid volume fractions of order 10^-3. The results are being analyzed.

Activity 3 Status as of May 27, 2020:
A laboratory scale solar receiver was developed to study heat transfer in concentrating solar power (CSP) systems in which solid ceramic particles are heated to provide thermal energy storage (TES). The 4 kW laboratory solar receiver is intended for evaluation of the impacts of particle material and size, particle flow rate and volume fraction on heat transfer to particles flowing through a vertical tube under gravitational acceleration. Gravity-flow of particles reduces the energy requirements of the system and system complexity compared to fluidized beds and rotating receivers. Experiments were conducted in the University of Minnesota solar simulator at commercially relevant temperature and solar concentration. This work presents data for commercially available 280 micron ceramic particles and solid volume fractions of order 10-3.

Activity 3 Status as of September 18, 2020:
The laboratory scale solar receiver, developed to study heat transfer in concentrating solar power (CSP) systems, was tested at commercially relevant temperature and solar concentration. For particle volume fractions of order 10^-3, heat transfer coefficients are of order 80 W/(m^2*K). Heat transfer to granular media is controlled in large part by contact resistance between particles and the heated surface and particle-to-particle heat transfer which can be affected by the effective thermal conductivity of the particles and interstitial gas and mixing. Heat transfer at the wall depends on the solid volume fraction near the wall. For flows with high solid volume fraction, particle-wall contact is high.

Activity 3 Status as of March 4, 2021:
Because of COVID-19, the University of Minnesota has reduced operations in laboratories. As a result, there were no experiments performed in the past period. Our research activities in the past period focused on analyzing the experiment data obtained prior to the pandemic.

Final Report Summary:
We have performed extensive tests on the solar particle receiver prototype under various conditions that replicate the high temperatures, gas atmosphere, and heating rates involved in a concentrated solar facility. A laboratory scale solar receiver has been developed to study heat transfer in concentrating solar power systems. Experiments were conducted with the University of Minnesota solar simulator at commercially relevant temperature and solar concentration. While more desirable experiments became impossible due to the outbreak of the COVID-19, the research results obtained already can greatly facilitate a meaningful transition from laboratory experiments to operations under concentrated solar radiation in the next step of research.

V. DISSEMINATION:

Description: The design and test results will be made available to the public via a web portal powered by the University of Minnesota, where the public can contribute ideas for further improvements. In particular, using the portal every step in our design process will be made publicly available in real time, inviting private and public entities to contribute ideas for further improvements, and at the same time extending the knowledge base. In the long term we aim at creating an open-source solar thermal project that can leverage the creativity of the people in Minnesota and beyond, and inspire future renewable energy start-ups. The results and findings of this project will be presented at national and international conferences on renewable energy attended by our research team and the involved personnel, as well as in scientific journal articles.

Status as of July 1, 2018:
The first results of the study of the unheated particle-laden duct flow are being incorporated in a manuscript to be submitted to a scientific journal. These results were also shared with specialists in concentrated solar power generation at the National Renewable Energy Laboratory, with the intent of developing a collaboration and attract federal funding towards the building and testing of large-scale particle solar receivers.

Status as of January 1, 2019:
The manuscript on the results of the unheated particle-laden duct flow was submitted to Journal of Fluid Mechanics (the leading journal in this scientific area of research), and is now under review. These results were also presented at the annual meeting of the American Physical Society, held in Atlanta, GA.

Status as of November 7, 2019:
The manuscript on the results of the unheated particle-laden duct flow in dilute conditions was published in Journal of Fluid Mechanics. The results of the unheated particle-laden duct flow in dense conditions were presented at the annual meeting of the American Physical Society, held in Seattle, WA.

Status as of May 26, 2020:
The results of the particle-laden duct flow in dilute conditions are being compiled in a paper to be submitted to Journal of Fluid Mechanics.

Status as of Sept 18, 2020:
We are continuing the redaction of the paper to be submitted to Journal of Fluid Mechanics, where the results of the particle-laden duct flow in dilute conditions will be included. We also started drafting another manuscript where the results for the particle-laden duct flow at denser concentration are reported.

Status as of March 4, 2021:
We have been continuing the revision of the paper for Journal of Fluid Mechanics. The analyses and presentation in the manuscript are much improved.

Final Report Summary:
While the plan of dissemination was refocused due to the pandemic, substantial efforts have been put into sharing the knowledge gained from this project. Our research results were shared with the specialists in concentrated solar power generation at the National Renewable Energy Laboratory of the Department of Energy. The findings of this project were presented at the national conference of the American Physical Society for multiple years. A paper has been published in the Journal of Fluid Mechanics (Fong, Amili and Coletti, JFM, 2019, vol. 872, pp.367-406), which is a leading journal in the field.

VI. PROJECT BUDGET SUMMARY:

A. Preliminary ENRTF Budget Overview:

***This section represents an overview of the preliminary budget at the start of the project. It will be reconciled with actual expenditures at the time of the final report.**

Budget Category	$ Amount	Overview Explanation
Personnel:	$236,049	1 graduate student at 27% FTE for each year for 3 years; 1 graduate student at 50% FTE for each 2 years and at 12.5% FTE for the last year; 1 research associate at 25% FTE for 2 years

Equipment/Tools/Supplies:	$9,716	Fused quartz window for radiation experiment in the receiver prototype; particulate material for radiation absorption; materials for constructing the receiver prototype
Capital Expenditures over $5,000:	$0	See explanation below
Others:	$4,235	Machining of components for receiver prototype
TOTAL ENRTF BUDGET:	**$250,000**	

Explanation of Use of Classified Staff: N/A

Explanation of Capital Expenditures Greater Than $5,000: The prototype of solar particle receiver will have a manufacturing cost (including materials and machining time) of about $10,000, but none of its components will have a cost greater than $5,000. After the end of the three-year project, the prototype might be further modified to pursue further funding at governmental level.

Total Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation: 2.375

Total Number of Full-time Equivalents (FTE) Estimated to Be Funded through Contracts with this ENRTF Appropriation: N/A

B. Other Funds: N/A

VII. PROJECT STRATEGY:

A. Project Partners:

Partners receiving ENRTF funding:

- Lian Shen, Professor, University of Minnesota, Project manager: $69,413 for salary of graduate student
- Filippo Coletti, Associate Professor, University of Minnesota, co-Investigator: $123,310 for salary of graduate student, equipment, and supplies
- Jane Davidson, Professor, University of Minnesota, co-Investigator: $57,276 for salary of research associate

Partners NOT receiving ENRTF funding : N/A

B. Project Impact and Long-term Strategy:

Although solar energy production in Minnesota has been growing, a substantial leap forward is urgently needed to comply with the 2013 Solar Energy Jobs Act, which requires investor-owned utilities in the state to produce 1.5% of their electricity from solar power by 2020. Current solar energy systems produce electricity at a cost 3 to 6 times higher than fossil fuels. This project will help impose a clean and low-cost renewable energy technology, demonstrating that solar thermal energy extraction is economically viable at our latitudes.

According to the National Renewable Energy Laboratory, Minnesota's annual potential of concentrated solar thermal energy in Minnesota exceeds 16 megawatt hours per acre of land, so that indeed each medium-size power plant using this technology would avoid the emission of 35,000 tons of CO2. Our project will be critical to exploit this largely untapped potential, helping to reduce carbon emissions to prevent further climate change, facilitating local power generation critical in rural areas, and improving energy affordability for everyone. Additionally, by making solar thermal energy possible in Minnesota, this technology will generate numerous green job opportunities.

If we can demonstrate, as our preliminary results indicate, that the target temperature and thermal efficiency can be achieved, it will mean that the solar particle receiver technology is technically feasible and economically viable. This would represent a breakthrough that will improve the renewable energy market in Minnesota, and in the whole Midwest. To be quantitative, for each square mile of solar thermal field we project that this technology can translate into 10 million kWh of produced energy. And since it is estimated that 10 cents are saved for each kWh of solar energy, this would result in one million dollar of cost saving per square mile of installed solar field.

Given such potential, this project will lay the groundwork for collaborations with companies members of the Minnesota Solar Energy Industries Association (MnSEIA), several of which have already partnered with St. Anthony Falls Lab, for the technology commercialization and the installation of the first solar thermal field in the state. Additional potential partners include 3M, which has recently expressed interest in the research conducted by our team in this area.

C. Funding History:

We have carried out preliminary research that indicates the feasibility of the proposed project (e.g. the evaluation of the high absorption efficiency of the silica carbide particles, as well as the theoretical calculations on the achievable thermal efficiency in the solar particle receiver). This work was performed by the investigators and through the engagement of undergraduate research assistants, without external funding.

VIII. REPORTING REQUIREMENTS:

- **The project is for 4 years, will begin on 07/01/17, and end on 06/30/21.**
- **Periodic project status update reports will be submitted January 1 and July 1 of each year.**
- **A final report and associated products will be submitted between June 30 and August 15, 2021.**

IX. VISUAL COMPONENT or MAP(S): See attached graphic.

Environment and Natural Resources Trust Fund
M.L. 2017 Final Project Budget

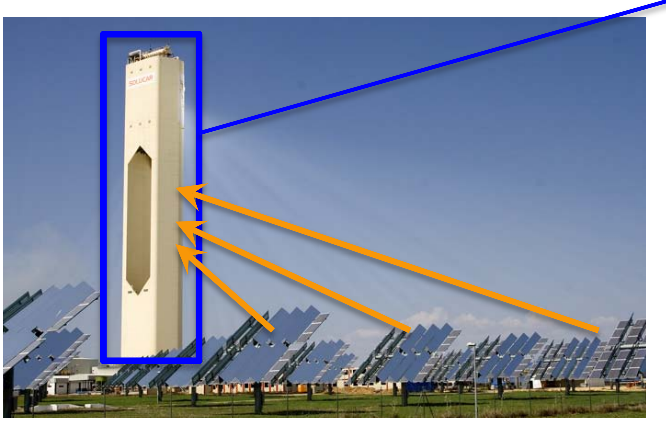
Project Title: Extraction of Solar Thermal Energy in Minnesota
Legal Citation: M.L. 2017, Chp. 96, Sec. 2, Subd. 07a
Project Manager: Lian Shen
Organization: Regents of the University of Minnesota
M.L. 2017 ENRTF Appropriation: $ 250,000
Project Length and Completion Date: 4 Years, June 30, 2021
Date of Report: 15 August 2021

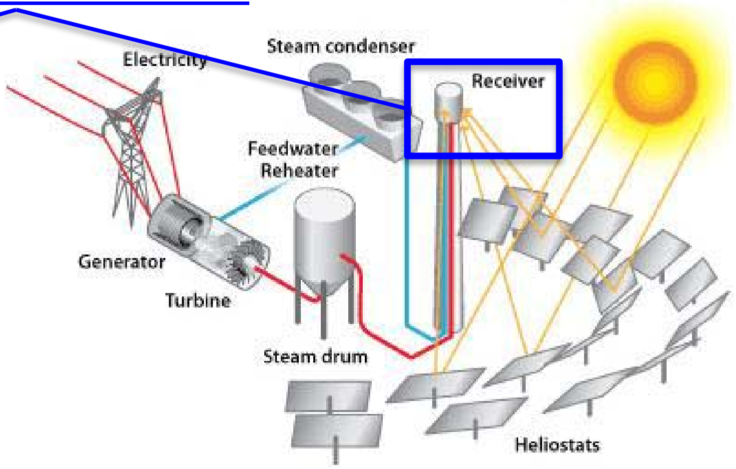
ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	TOTAL BUDGET	AMOUNT SPENT	TOTAL BALANCE
BUDGET ITEM			
Personnel (Wages and Benefits)	$236,049	$236,049	$0
50% Graduate Student, $59,676 salary + $43,761 fringe			
27% Graduate Student, $43,610 salary + $31,726 fringe			
25% Research Associate, $42,839 salary + $14,437 fringe			
Lab Supplies	$9,716	$9,716	$0
Fused quartz window with 99.5% transparency in infrared radiation ($4,000); materials for constructing solar receiver prototype ($3,000); gas supplies to run solar simulator and relative instrumentation ($2000); silica carbide particulates with high absorption properties $716			
Other	$4,235	$4,235	$0
Machining of prototype components, performed in the College of Science and Engneering Workshop $4,235			
COLUMN TOTAL	**$250,000**	**$250,000**	**$0**

Filippo Coletti, Jane Davidson & Lian Shen, University of Minnesota

Enabling extraction of solar thermal energy in Minnesota

Solar Thermal Energy can be extracted efficiently using Solar Particle Receivers





OBJECTIVE: build and optimize a new **Solar Particle Receiver**

STRATEGY: couple **laboratory** and **computer** simulation

GOAL: enable **solar thermal power** in Minnesota

Prototype testing

validate

Computer simulations

provide

Optimized design

verified by