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ABSTRACT

High fidelity computational models of thermocline-based thermal energy storage (TES) were developed. The research goal was to advance the understanding of a single tank nanofludized molten salt based thermocline TES system under various concentration and sizes of the particles suspension. Our objectives were to utilize sensible-heat that operates with least irreversibility by using nanoscale physics. This was achieved by performing computational analysis of several storage designs, analyzing storage efficiency and estimating cost effectiveness for the TES systems under a concentrating solar power (CSP) scheme using molten salt as the storage medium. Since TES is one of the most costly but important components of a CSP plant, an efficient TES system has potential to make the electricity generated from solar technologies cost competitive with conventional sources of electricity.

CONTENTS

ABSTRACT .... **III**

EXECUTIVE SUMMARY **1**

1 INTRODUCTION **2**

2 BACKGROUND **2**

3 RESEARCH **3**

3.1 Flow distributor for a thermocline TES system 4

3.2 Impact of nanofluidized TES medium on the thermocline stability 4

3.3 High-order scheme for accurately predicting the thermocline behavior during charging, discharging, and idling cases 4

3.4 High temperature TES medium 5

4 EDUCATION **5**

5 CONCLUSION **7**

6 BIBLIOGRAPHY **8**

7 LIST OF ACRONYMS AND ABBREVIATIONS **10**

EXECUTIVE SUMMARY

In this project, the research and education plan centered on preparing the next generation scientists and engineers, especially those from underserved groups, with the integrative knowledge base, collaborative interdisciplinary experiences, as well as the technical, professional, entrepreneurship, and personal skills, needed to lead innovation in renewable energy technology and renewable energy market development. The research goal was focused on performing computational analysis for designing an efficient and cost-effective thermal energy storage (TES) system for concentrating solar power (CSP) using molten salt as the storage medium and latest developments in the nanotechnology (e.g. nanoparticles suspended in molten salt). Several thermal storage medium and systems and liquid medium have been used; however, their usage has been restricted by costs ($.06 per kWh) of production, heat conductivity issues, heat capacity limitations, and temperature range of operation. An efficient TES system can contribute to making electricity generated from solar technologies cost competitive with conventional sources of electricity. Major research milestones of the project are

- Developed Eulerian granular models for TES using FLUENT investigation capabilities to advance the understandings of the experimental studies on the heat storage capacity of the nitrate molten salts at high temperatures (200-600^{0}C),
- Developed an optimal pipe network distributor for a single tank thermocline TES, and
- Developed a high temperature (800-1200^{0}C) encapsulated Phase Change Material (PCM) particle based TES which also be used as a Heat Transfer Fluid (HTF) (U.S. Patent US20160194543 A1).

The targeted educational activities produced many qualified scientists and engineers with B.S., M.S., and Ph.D. degrees and many of them are from under-represented communities with different backgrounds who share a common interest in renewable energy. Major education milestones of the project are

- 2 students graduated with Ph.D. degree,
- 3 students graduated with M.S. degree,
- 6 Undergraduate Research Assistants (UG RA) in the project related areas, and
- many internships at Department of Energy (DOE) national laboratories in CSP focused areas at National Renewable Energy Lab (NREL) and Sandia National Labs (Sandia).

The milestone was achieved through deliberate development of team, communication, research, and other skills and knowledge in solar energy; targeted solar energy internships at the National Labs; and student-centered activities in collaboration with Texas A&M. The educational activities involved many student and faculty visits and summer research at Texas A&M's Texas Engineering Experimentation Station (TEES) and National Renewable Energy Lab (NREL)'s Concentrating Solar Power (CSP) program. These activities strengthened the research and educational capabilities of UTEP in renewable energy technology and renewable energy market development and encouraged our students to excel in science and technology by providing them with practical experience and training through research projects in solar energy technology and solar energy market development in collaboration with national lab and a Tier One university.

1 INTRODUCTION

The research objectives focused on design an efficient thermal energy storage (TES) system utilizing sensible-heat that operates with least irreversibilities (i.e. with minimum generation of entropy) by using nanoscale physics (i.e. nanoparticles, nanocoatings, & nanofins). Recent experiments with nanoparticles suspended in liquid at minute concentrations (less than 1% by volume) have led us to the creation and investigation of a new potential storage medium consisting of slurry of nanoparticles. The computational investigation was based on empirical results obtained from various literatures for the thermal capacity and cyclic efficiency (charging and discharging) by enhancing the fundamental thermal characteristics, namely specific heat and thermal conductivity/ diffusivity. The thermodynamic properties of such systems however are not well understood. We believe that there is stronger need than ever to perform high fidelity computational analysis of such systems and produce next generation qualified engineers and scientists for Concentrating Solar Power (CSP) and other solar systems to produce energy at affordable prices.

The goal of this project was to develop research and education capabilities at UTEP in solar energy technology-related research. The development focused on developing high fidelity computational technologies to understand and design an advanced TES for a CSP; encouraging students from underrepresented communities to participate in the research program; and enlarging the personnel resources in solar energy technology by offering a solar energy course every year.

2 BACKGROUND

Direct solar energy conversion, in particular Concentrated Solar Power (CSP), has become an attractive option in view of rise in conventional energy costs[1]. Thermal energy storage (TES) system is crucial for enhancing the reliability and reducing the operational cost of CSP[2], [3]. TES can be implemented in several ways – such as solid or phase change mediums or liquid as a storage medium for later use. The system can be employed to balance energy demand between daytime and night or to accommodate for any changes in solar energy radiation (e.g. cloudy day). An efficient low-cost high-capacity TES system will give rise to lower levelized energy cost[4], [5]. The TES system is the preferred choice because its levelized cost is cheaper than a low-efficiency peaking gas turbine power plant that is usually used to make up for the peak demand (these gas turbine units have lower fixed costs but higher operational costs). The main problems of a TES design are to 1) establish a suitable heat transfer surface in order to get fast transfer of heat to and from the TES unit; and 2) avoid heat loss to the surroundings so that leakage time is long compared with the required storage time. Finding a suitable medium at an affordable price which has higher specific heat capacity and which can operate at 500ºC or above is desired by a CSP plant has been a challenge.

Two tank storage systems are the most common design for thermal energy storage. In two tank TES system, we use hot and cold tanks. In a single tank TES system, we use only one tank to store both hot and cold fluids. Here, hot and cold fluids are separated by a thermocline[6]–[9]. Usually molten salt or salt eutectic are used for the storage medium but it also provides opportunities for enhancing the thermal energy storage capacity including by using the filler or encapsulated phase change materials. Scientists and researchers however are still working to find an efficient and cost effective technology for storing solar energy and converting it to useable form for a CSP plant. Various technologies have been proposed for producing electricity in large scale from CSP plant. Yang and Garimella [9] looked into the thermal characteristics of a single tank thermocline under different environmental boundary conditions. Mawire and Mcpherson [10] developed an oil pebble bed for TES system with constant temperature and variable electrical power. John et al. expanded the concept of storing thermal energy by using filler material as the storage medium in a single tank thermocline [11]. Shin and Banerjee introduced nanoparticles in salt eutectics to increase the specific heat capacity in a single tank thermocline TES system[12]. Molten salts were studied by Jones et al. [13], [14], as one of the medium for the TES system.

Since in a two tank system, hot and cold fluid are allocated into two different tanks, a big shortcoming of this system is that it is not cost effective and it requires large amounts of space. As an attempt to overcome these shortcomings, a single tank is introduced. A single tank TES option provides a cheaper alternative to the two tank system. In this this system, both the hot and cold fluid are placed in the same tank. In this system the two regions - hot and cold temperature region is disjoined for the entire operating period. These two regions are separated by a temperature gradient known as thermocline, with the hot fluid positioned at the top and the cold fluid at the bottom of the tank. When the system is charged the cold fluid is drained from the bottom of the tank, heated up by the solar field and returned through the top of the tank. In the discharging period the hot fluid is drawn from the top of the tank and cooled down while passing through the power conversion equipment [1]. During the charging-discharging cycle, the thermocline region should not be disturbed. So the main concern is to retard the mixing of hot and cold fluid introduced by the inlet flows.

Sandia National Laboratories, in collaboration with the National Renewable Energy Laboratory (NREL), have done comparisons between the more conventional two tank storage systems and single tank thermocline storage systems. These studies have shown that thermocline-based energy storage configurations may be the least-cost energy storage option. The thermocline system was approximately 35% cheaper than the two tank storage system as it does not require any heat exchanger and the setup occupies less space compared to the two tank storage system. One of the major challenges for the single tank thermocline is actually maintaining the thermocline region in the tank, so that it does not spread out to occupy the entire tank. Since the thermocline is a horizontal surface, we must introduce hot and cold fluid in such a way that it does not disturb the thermocline. If the fluid is introduced in a jet stream, it will cause the thermocline to disrupt as it will mix the hot and cold fluids into a homogeneous medium. With that in mind, the flow must be distributed evenly in a horizontal uniform profile in order to use the hot fluid for power production and return the cold fluid back into the tank, and vice versa.

The purpose of this study to design an efficient distributor for a thermocline based TES system. An ideal distributor will minimize the thermocline spreading and hence maximize the useable form of thermal energy storage in a single tank system. Here, we investigate the impact of various distribution configurations and present an optimal configuration. In this study, we consider the impact of fluid dynamics only. Near the changing and discharging boundary, inertial and viscous effects of the fluid dynamics are more important in maintaining the thermocline. The limitation of this study is that the thermocline spreading due the thermal diffusivity is ignored. Thermocline spreading would be important to measure the degradation of the thermocline over many changing and discharging phases. Our study therefore would be limited to achieving the best behavior in a single charging or discharging mode.

3 RESEARCH

Thermal energy storage system, when combined with a CSP plant, has potential to produce electricity at a cost-competitive rate to traditional sources of electricity production. In single tank

TES system both the hot fluid and cold fluid settle in the same tank. The region of contact of these two fluids is called thermocline. Preservation of this thermocline region in the cylindrical tank during charging and discharging cycles depends on the uniformity of the velocity profile at any horizontal plane. So to maintain this thermocline region, a pipe flow distributor was placed near the inlet and outlet of the cylindrical tank. To optimize the efficiency of this single tank TES system is to increase the thermo-physical properties of heat transfer fluid. This addition will result in harnessing solar energy by increasing thermal efficiency of the thermodynamic cycles. Following subsections summarizes the results that were performed under this project.

3.1 Flow distributor for a thermocline TES system

A single tank TES system consists of a thermocline region which produces the temperature gradient between hot and cold storage fluid by density difference. Preservation of this thermocline region in the tank during charging and discharging cycles depends on the uniformity of the velocity profile at any horizontal plane. Our objective is to maximize the uniformity of the velocity distribution using a pipe-network distributor by varying the number of holes, distance between the holes, position of the holes and number of distributor pipes. Methods for optimizing a thermocline in a thermal energy storage fluid within a thermal energy storage tank were disclosed by Mathur and Kasetty [15]. For simplicity, we consider that the diameter of the inlet, main pipe, the distributor pipes and the height and the width of the tank are constant. We use Hitec® molten salt as the storage medium and the commercial software Gambit 2.4.6 and Fluent 6.3 for the computational analysis. We analyze the standard deviation in the velocity field and compare the deviations at different positions of the tank height for different configurations. Since, the distance of the holes from the inlet and their respective arrangements affects the flow distribution throughout the tank; we investigate the impacts of rearranging the holes position on flow distribution. Impact of the number of holes and distributor pipes are also analyzed. We analyze our findings to determine a configuration for the best case scenario.

3.2 Impact of nanofluidized TES medium on the thermocline stability

Adding of nanoparticles, in the heat transfer fluid give rise of this thermo-physical properties i.e. thermal conductivity (k) and specific heat capacity(C_p). Hitec® molten salt is used as the base-fluid and synthesized with five different types of nanoparticles (SiO_2, Al_2O_3, Fe_3O_4, ZnO and Ag) with different concentrations. The values of effective k and C_p are calculated for the new Hitec® nanofluid. The doping of nanoparticles results in higher k and C_p when compared to the base fluid. Higher C_p is expected to improve the thermal storage capacity but higher value of k is expected to increase the thermal diffusivity, thereby affecting the performance of the thermocline. The diffusivity depends on the ratio of k to C_p and density of the effective properties. So there is a need to balance the effective properties to improve thermal storage performance. The total energy storage capacity is then checked by finite volume based computational fluid dynamics software. The simulation shows how the performance of the nanofluid changes at different concentrations in a single tank TES system during its charging-discharging cycle.

3.3 High-order scheme for accurately predicting the thermocline behavior during charging, discharging, and idling cases

The temperature distribution in the thermocline tank takes on a step function shape initially with the colder temperature on the bottom, the hotter temperature on top and a step-wise transition at their interface. Over time, the step change in temperature (and density) gradually spreads due to thermal diffusion in the fluid. A key performance indicator would be the effectiveness with which the retrieved energy from TES can be used downstream for power production. The quality of the stored energy is lost on account of spread of the thermocline region, mixing of the fluid at entrance and exit, and other thermal losses to the surrounding. In this work, thermocline tank is modeled using commercially available computational fluid dynamics (CFD) software. Tanks with various filler geometries and configurations are modeled. Relative performances of the various TES concepts are evaluated and recommendations for further evaluations are provided. The research is proposed to improve efficiency by utilizing sensible-heat that operates with least irreversibility. Effective thermal diffusion was obtained by performing a set of computational fluid dynamics 3D simulations for hexagonal symmetry. The resulting thermocline system hence can be effectively represented by 1D advection-diffusion equation by introducing an effective thermal diffusivity. Using this effective thermal diffusivity, a thermocline spreading model for the thermocline is presented based on an advection-diffusion solver.

3.4 High temperature TES medium

High temperature storage increases power cycle efficiency, which is equivalent to reduce the solar field cost and size, and increases storage energy density. However, the high temperature storage is still not technologically viable at this moment. Our study presents preliminary studies on developing an innovative approach to develop an engineered material that possess high heat capacity and thermal conductivity for temperatures from 700°C to 1000°C. The engineered material is achieved by assuming an alloy melt encapsulated in SiC capsules containing a thin graphite layer of 10-15mm diameter at approximately 1000°C [16]. The encapsulated alloy melt uses the enthalpy of fusion/solidification, as well as its heat capacity transfer; it stores and releases heat from 800°C to 1200°C during the day time. The storage media uses low-cost, highly-stable solid material (sand, silica) that can be made to behave like a fluid using fluidization and other solid-particle transport mechanism. For charging/discharging processes, air is directly set in contact with the storage media which provides a heat transfer medium for the particles[16]. In the storage mode, stagnant solid particles can be self-insulated to hold the heat. Also for the simulation study, materials falling at an ambient condition will be considered as a main focus.

4 EDUCATION

One of the major objectives of the proposal was to develop workforce in solar energy related fields with a focus on under-represented minority. This objective was achieved more than what was proposed in the proposed tasks. They were achieved by organizing summer trip to Texas A&M and NREL and creating summer interns position for many students by leveraging various from DOE, NREL, and University personnel and financial resources (e.g., DOE SULI & FaST program). This resulted in several peer reviewed conference and journal manuscripts authored/co-authored by the participating students as tabulated below.

Name	Total
Degree	
Ph. D. degree awarded	2
M. S. degree awarded	3
U. G. RA	6
Internships	
SULI - NREL	3
On campus research	3
UG RA	6
SANDIA	3
Visit faculty (DOE-VFP)	1
Publications	
Journals	3
ASME conferences	6
Southwest Energy Symposium	6
Presentations	
COURI	2
ASME (FEDSM, Energy Sustainability, IMECE)	8
Southwest Energy Symposium	6
ASEE	2

The students extensively made scholarly contributions through peer reviewed international journals and conference proceedings. Below is the short list of the contributed work

<u>Peer Reviewed Journals:</u>

- V. Kumar, S. Afrin*, J. Ortega*, A. Sepulveda*, L. D Juan*, A. Jesus*, A. Dante*, H. Lu, "Development and evaluation of a prototype concentrating solar collector with thermocline based thermal energy storage for residential thermal usage", *Journal of Renewable and Sustainable Energy*, 5, 053144 (2013).
- S. Afrin*, V. Kumar, D. Bharathan, G.C. Glatzmaier, Z. Ma., "Computational analysis of a pipe flow distributor for a thermocline based thermal energy storage system", *Journal Solar Energy Engineering,* 136(2), 021010, (2013).
- E. Busquets*, V. Kumar, J. Motta*, R. Chacon*, & H. Lu, "Thermal analysis and measurement of a solar pond prototype to study the non-convective zone salt gradient stability", *Journal of Solar Energy*, 86-5, 1366–1377 (2012).

<u>Peer Reviewed Conference Proceedings:</u>

- N. Hossain, S. Afrin, J. Ortega, V. Kumar, D. Banerjee, "Numerical analysis of total energy storage of nanofluidized heat transfer fluid in thermocline thermal energy storage system", ASME ES-FuelCell2014-6451 (2014).

- S. Afrin, J. Ortega, C. Ho, V. Kumar, "Modeling of a High-Temperature-Serpentine External Tubular Receiver Using Supercritical CO_2", ASME ES-FuelCell2014-6376 (2014).
- P. Delgado, V. Kumar, "A stochastic galerkin approach to uncertainty quantification in poroelastic media", ASME FEDSM2014-21577 (2014).
- S. Afrin*, J.D. Ortega*, V. Kumar, D. Bharathan, "A computational analysis: A honeycomb flow distributor with porous approximation for a thermocline thermal energy storage system", ESFULECELL2013-18342 (2013).
- A. Sepulveda, S. Shantha-Kumar, V. Kumar, A. Bronson, Z. Ma, "Feasibility studies of encapsulated fluidized particles with phase change materials as high temperature (1200^{o}c) heat transfer fluid for the solar tower", ASME FEDSM2013-16151 (2013).
- J.Ortega*, S. Afrin*, V. Kumar, J. Gomez, "A computational analysis on the impact on the effective thermal properties of a nano-fluidized in a single-tank thermocline solar salt thermal energy storage system", ASME FEDSM2013-16434, Incline Village, NV (2013).
- S. Afrin*, E. Cordero, S. Rosa, V. Kumar, D. Bharathan, G.C. Glatzmaier, Z. Ma., "Computational analysis of a pipe flow distributor for a thermocline based thermal energy storage system", ASME 6th International Conference on Energy Sustainability, ESFuelCell2012-91069, San Diego, CA (2012).

<u>Other conferences:</u>

- A. Cabral, S. Afrin, V. Kumar, "Comp. Analysis of Flow Distribution for a One Tank Thermal Energy Storage System", 3rd Southwest Energy Science & Engg Sym, Spring 2013.
- A. Rios, J. Ortega, V. Kumar, "Numerical Analysis of Total Energy Storage of Nanofluidized Heat Transfer Fluid In Thermocline Thermal Energy Storage System", 3rd Southwest Energy Science and Engineering Symposium, Spring 2013.
- M. Chaidez, S. Afrin, V. Kumar, "Numerical Analysis of Total Energy Storage of Nanofluidized Heat Transfer Fluid in Thermocline Thermal Energy Storage System", 3rd Southwest Energy Science and Engineering Symposium, Spring 2013.
- S. Rosa, A. Sepulveda, V. Kumar, "Feasibility Analysis of Solid Particles as a Thermal Energy Storage Medium Using Fluidization Process", COURI Symp., Spring 2012, 04/2012.
- C. L. Guevara, K. Kumar, V. Kumar, "High Fidelity Thermocline Tracking Algorithm Using Weighted Essentially Non-Oscillatory Schemes", COURI Symposium, Spring 2012, 04/2012.
- J. D. Ortega, V. Kumar, "Computational Models of Sub-Divided Thermal Energy Storage Tanks used in Concentrating Solar Power Plants with Parabolic Trough Collectors", COURI Symposium, Spring 2012, 04/2012.
- S. Afrin, V. Kumar, "Model of a Pipe Flow Distributor for Single Tank Thermocline Thermal Storage System", 2nd Southwest Energy Science & Engg. Symp., Spring 2012.
- E. Busquets, R. Chacon, G. Ceballos, V. Kumar, and H. Lu, "Computational thermal analysis and measurement of the salt gradient stability in a solar pond", 1st Southwest Energy Science and Engineering Symposium, Spring 2011.
- J. Motta-Mena, E. Busquets, and V. Kumar, "Scalable three-dimensional geometry preprocessor for molecular dynamics analysis", 1st Southwest Energy Science and Engineering Symposium, Spring 2011.

5 CONCLUSION

High fidelity computational model was developed and used to investigate the efficiency of thermal energy storage (TES) systems. It was observed that the velocity distribution is significantly influenced by the number of distributor pipes and their arrangements and noticed that the changed fluid and thermal properties of nanofluid systems must be considered to design an efficient TES system. The 7 pipes configuration with 140 holes produced most uniformity in the velocity distribution whereas 6 pipes with 104 holes produced least uniformity in the velocity distribution because of the viscous resistance for the flow through various pipe and the interactions of the flow exiting through various distribute holes play a balancing role in the determining the uniformity. The designed was employed in a senior design project. The project required designing, building, and testing. Total energy collected in the tank (when fully charged) was calculated to be 3 kWh using the average temperature based on the test performed in a regular winter month.

A novel TES media was developed for high temperature TES needs which can be used as both the HTF and TES medium with operating temperatures ranging from 300^{o}C to 500^{o}C. Increase in heat capacity and thermal conductivity values of the molten salt has been reported by doped with SiO_2, Al_2O_3, CuO, Ag and ZnO nanoparticles at different concentrations. This media was investigated for the thermocline system which expected to be about 35% cheaper compared to the two-tank storage currently used. Further enhancement has been proposed for higher temperature (800-1000°C) though thermodynamic analysis for several binary and ternary alloys and engineering their composition mixture. The engineered media are achieved by encapsulating alloys inside solid particles capable of operating at temperatures >1300°C. We conclude that the 56%Al-44%Si alloy encapsulated in SiC particles possess desired melting point and possess high heat capacity.

6 Bibliography

[1] G. Glatzmaier, "Future Trends for CSP Thermal Energy Storage Seminar," 2011.

[2] U. Herrmann and D. W. Kearney, "Survey of Thermal Energy Storage for Parabolic Trough Power Plants," *J. Sol. Energy Eng.*, vol. 124, no. 2, p. 145, 2002.

[3] B. Zalba, "Review on thermal energy storage with phase change: materials, heat transfer analysis and applications," *Appl. Therm. Eng.*, vol. 23, no. 3, pp. 251–283, 2003.

[4] H. Price, D. Brosseau, D. Kearney, and B. Kelly, "DOE advanced thermal energy storage development plan for parabolic trough technology," 2007.

[5] M. Medrano, A. Gil, I. Martorell, X. Potau, and L. F. Cabeza, "State of the art on high-temperature thermal energy storage for power generation. Part 2—Case studies," *Renew. Sustain. Energy Rev.*, vol. 14, no. 1, pp. 56–72, Jan. 2010.

[6] J. T. Van Lew, P. Li, C. L. Chan, W. Karaki, and J. Stephens, "Analysis of Heat Storage and Delivery of a Thermocline Tank Having Solid Filler Material," *J. Sol. Energy Eng.*, vol. 133, no. 2, p. 21003, 2011.

[7] S. Afrin, V. Kumar, D. Bharathan, G. Glatzmaier, and Z. Ma, "Computational Analysis of a Pipe Flow Distributor for a Thermocline Based Thermal Energy Storage System," *J. Sol. Energy Eng.*, vol. 136(2), 2013.

[8] J. E. Pacheco, S. K. Showalter, and W. J. Kolb, "Development of a molten-salt thermocline

thermal storage system for parabolic trough plants," 2001.

[9] Z. Yang and S. V. Garimella, "Thermal analysis of solar thermal energy storage in a molten-salt thermocline," *Sol. Energy*, vol. 84, no. 6, pp. 974–985, Jun. 2010.

[10] A. Mawire and M. McPherson, "Experimental and simulated temperature distribution of an oil-pebble bed thermal energy storage system with a variable heat source," *Appl. Therm. Eng.*, vol. 29, no. 5–6, pp. 1086–1095, 2009.

[11] E. John, M. Hale, and P. Selvam, "Concrete as a thermal energy storage medium for thermocline solar energy storage systems," *Sol. Energy*, vol. 96, pp. 194–204, 2013.

[12] D. Shin and D. Banerjee, "Enhancement of specific heat capacity of high-temperature silica-nanofluids synthesized in alkali chloride salt eutectics for solar thermal-energy storage applications," *Int. J. Heat Mass Transf.*, vol. 54, no. 5–6, pp. 1064–1070, 2011.

[13] G. Kolb, "Concentrating solar power : the 'other' solar. A systems perspective," Sandia National Laboratories, 2004.

[14] J. De Andrade, E. S. Böes, and H. Stassen, "Computational study of room temperature molten salts composed by 1-alkyl-3-methylimidazolium cations - Force-field proposal and validation," *J. Phys. Chem. B*, vol. 106, no. 51, pp. 13344–13351, 2002.

[15] A. Mathur and R. Kasetty, "Thermal energy storage system comprising optimal thermocline management," US8554377, 2013.

[16] A. Sepulveda, S. Shantha-Kumar, V. Kumar, A. Bronson, and Z. Ma, "Feasibility studies of encapsulated fluidized particles with phase change materials as high temperature (1200C) Heat Transfer Fluid for the Solar Tower," in *ASME FEDSM2013-16151*, 2013.

7 LIST OF ACRONYMS AND ABBREVIATIONS

Ca: Capillary number
CFD: Computational Fluid Dynamics
CSP: Concentrating Solar Power
DOE: Department of Energy
EERE: Energy Efficiency and Renewable Energy
HPC: High Performance Computing
HTF: Heat Transfer Fluid
NREL: National Renewable Energy Lab
Re: Reynolds number
MNA: Modified Nodal Approach
Sandia: Sandia National Laboratories
TES: Thermal Energy Storage
UTEP: University of Texas at El Paso