



Напълно природосъобразно иновативно решение за безвъглищна работа на ТЕЦ

Най-евтиното продължаване работата на единственият базов национален енергиен ресурс (ТЕЦ), вместо с пара от въглища - с парогенератори от електро-термоакумулация на излишния ток от ВЕИ. Те са перспективна алтернатива, не само у нас. Устойчивото техническо решение гарантира националната сигурност с местни ресурси, уплътнява наличните инженерни съоръжения и инфраструктура и запазва работни места. То се реализира с налични суровини, вместо с вносни и скъпи редкоземни метали. Иновативният проект е от световна патентна новост от май 2024 г., както е посочено в официалния доклад от Патентното ведомство в приложения файл.

Синергичните ползи са поне четири:

- Първата е енергоакумулация на излишъците от ВЕИ електричество. Излишъците са сериозен проблем за елмрежата, поради повишаването на честотата й..
- Втората е природосъобразна електрогенерация в ТЕЦ и другаде, без ползване на каквито и да е било нови енергийни ресурси.
- Третата е увеличаване гъвкавостта на елестросистемата за много по-лесно поддържане на баланса й.
- ТЕЦ са, и остават, единственият национален енергиен ресурс (без или с въглища). Токът от АЕЦ става вече скъп, а глобалното затопляне намалява водния ресурс за ВЕЦ.

Иновативният проект е пъти по-евтин от ПАВЕЦ. Той се изгражда в кондензационни и когенерационни ТЕЦ-ове. Както и в децентрализирана електросистема. Примерно до подстанции, възлови трафопостове и др., включително и под терена.

Кратко видеопредставяне на “Реверсивна термична енерго-акумулираща система за излишъците от ВЕИ с електро-парогенерация за флуидни електрогенератори” вижте на: <https://www.youtube.com/watch?v=jR7LflrbEbQ&t=92s>



Наш знак:	СпИС – 605	15/05/2024
Ваш знак:		

До
Георги Димитров Тончев
ж.к. Южен парк, блок 1, вх. Д, ап.
1
гр. София

**Искане за проучване за новост на изобретение с наименование
„Реверсивна термична енерго- акумулираща система за излишъците от
ВЕИ с електро- парогенерация за флуидни електрогенератори”**

Патентното ведомство Ви уведомява, че във връзка с Ваше искане СпИС-605 от 07.05.2024г. е извършено проучване въз основа на:

- ☒ описание
- ☒ претенции
- ☒ чертеж

предоставени от Вас

Класове по МПК : H02J15/00; H02S40/44; H02S10/10; F01K3/02; F03G6/00; F25B27/00

Класове по КПК: Y02E10/46; Y02E60/14; Y02E10/50; Y02E10/60; H02S40/00; H02S40/44; F01K23/04; F01K3/12; F03G6/00; F03G6/001; F03G6/06; F03G6/068; F03G6/071; F03G6/092

База данни: IPAS; esp@cenet; Epoque Net, Internet

При проучването:

- ☒ са намерени следните документи, които са посочени в приложения доклад:

JP2016142272 (A); CN104734323 (A); BG113495 (A); ES2385894 (A1)

ПРИЛОЖЕНИЕ:

- ☒ Доклад
- ☒ Становище за новост
- ☒ Копия от цитираните документи

Desislava
Aleksandrova
Petrova-
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ПАТЕНТНО ВЕДОМСТВО НА РЕПУБЛИКА БЪЛГАРИЯ



ПАТЕНТНО ВЕДОМСТВО НА РЕПУБЛИКА БЪЛГАРИЯ

ДОКЛАД ОТ ПРОУЧВАНЕ

ПРОУЧВАНЕ Вх. № СпИС-605/07.05.2024г.

„Реверсивна термична енерго- акумулираща система за излишъците от ВЕИ с електро- парогенерация за флуидни електрогенератори ”

I. Уточнен класификационен индекс по

МПК H02J15/00; H02S40/44; H02S10/10; F01K3/02; F03G6/00; F25B27/00

КПК Y02E10/46; Y02E60/14; Y02E10/50; Y02E10/60; H02S40/00; H02S40/44; F01K23/04; F01K3/12; F03G6/00; F03G6/001; F03G6/06; F03G6/068; F03G6/071; F03G6/092

II. ОБЛАСТ НА ПРОУЧВАНЕ:

Минимален обхват на проучване

Вид класификация:

Класификационен индекс:

МПК / КПК

МПК H02J15/00; H02S40/44; H02S10/10; F01K3/02; F03G6/00; F25B27/00

КПК Y02E10/46; Y02E60/14; Y02E10/50; Y02E10/60; H02S40/00; H02S40/44; F01K23/04; F01K3/12; F03G6/00; F03G6/001; F03G6/06; F03G6/068; F03G6/071; F03G6/092

Бази данни, в които е извършено проучването

IPAS; esp@cenet; Epoque Net; Internet

III. Релевантни документи

Категория	Цитиране на документите с посочване на релевантните части	Релевантни претенции
A	JP2016142272 (A), (GENERAL ELECTRIC TECHNOLOGY GMBH), публикуван на 08.08.2016 г.	1 - 14
A	CN104734323 (A), (ZHUHAI GREE ELEC APPLIANCES), публикуван на 24.06.2015 г.	1 - 14
A	BG113495 (A), (BADZHINKOV MLADEN [BG]), публикуван на 15.09.2023 г.	1 – 14
A	ES2385894 (A1), (BONONATO CLAVERO DIEGO ANGEL [ES]), публикуван на 02.08.2012 г.	1-14

Категория на документа

X – документът е от особено значение; претендираното изобретение няма новост или изобретателска стъпка, когато документът се разглежда самостоятелно
Y – документът е от особено значение; претендираното изобретение няма изобретателска стъпка, когато документът се комбинира с един или повече други документи и тази комбинация е очевидна за специалист в областта
A – документ, отразяващ нивото на техниката, който не е от особено значение
D – документ, цитиран в описанието

O – неписмено разкриване, използване, прилагане, докладване или демонстриране
P – документ, публикуван преди датата на подаване в България, но след приоритетната дата
E – по-рано подадена българска заявка, но публикувана на или след датата на подаване
L – документ, който може да предизвика съмнение относно приоритета на претенциите или който е цитиран с цел установяване датата на публикация на друг документ или друга специална причина (както е посочено)
& - документ от една патентна фамилия

Дата: 15/05/2024 г.

Име: Десислава Иванова

Desislava Aleksandrova
Petrova-Ivanova
Date: 2024.05.15
08:26:00 +03:00

Десислава Иванова
Главен експерт ДЕЗИПМПД



СТ А Н О В И Щ Е

ОТНОСНО: проучване за новост на изобретение с
наименование „Реверсивна термична енерго- акумулираща система за
излишъците от ВЕИ с електро- парогенерация за флуидни електрогенератори ”
СпИС – 605/07.05.2024 г.

Към искането за проучване са приложени описание, претенции и чертеж.
Формулирани са една независима претенция и тринадесет зависими претенции.

Съгласно независима претенция 1 проучването се отнася до реверсивна термична енерго- акумулираща система за излишъците от ВЕИ с електро- парогенерация за флуидни електрогенератори, включваща устройство за събиране на атмосферна вода, интегрирано между най-малко два наклонени фотоволтаични панела, разположени един зад друг. Устройството за събиране на атмосферна вода е монитирано между панелите, над резервоар за съхранение на вода, разположен между долните ръбове на фотоволтаичните панели, към които неподвижно са монтирани светлинни рефлектори. Общ електрически извод от фотоволтаичните панели, през управляем токоразпределител, е свързан към първи електрически вход на термоакумулиращия блок. Общ електрически извод от ветроелектрогенератори през управляемия токоразпределител, е свързан към втори електрически вход на термоакумулиращия блок. Общ електрически извод от хидрокинетични електроцентрали през управляемия токоразпределител, е свързан към трети електрически вход на термоакумулиращия блок, чиито флуиден извод високо налягане през първи флуиден контролер , е съединен с флуиден вход на флуидно- електрически конвертор за високо налягане. Флуиден извод ниско налягане от термоакумулиращия блок през втори флуиден контролер, е съединен с флуиден вход на флуидно- електрически конвертор за ниско налягане, чиито електрически извод през първи реверсивен електропреобразовател, е присъединен към външна електрическа мрежа. Електрически извод от флуидно- електрическия конвертор за високо налягане през втори реверсивен електропреобразовател също е присъединен към външната електрическа мрежа. Първи сигнален вход на интелигентен оптимизиращ управленски процесор е безжично свързан с извод от комбиниран датчик за атмосферните параметри. Втори сигнален вход на интелигентния оптимизиращ управленски процесор е безжично свързан с извод от комбиниран датчик за термоелектрически параметри на флуидно-електрически конвертор за високо налягане. Трети сигнален вход на интелигентния оптимизиращ управленски процесор е безжично свързан с извод от комбиниран датчик за термоелектрически параметри на флуидно- електрическия конвертор за ниско налягане, а "изход-вход" от първи реверсивен електропреобразовател през първа реверсивна шина е свързан с първи "вход- изход" на управляемия токоразпределител. "Изход- вход" от втори реверсивен електропреобразовател през втора реверсивна шина е свързан с втори "вход- изход" на управляемия токоразпределител. Управленски извод от управляемия токоразпределител е свързан с дистанционно управляем радиомодул.

Съгласно зависима претенция 2, фотоволтаичните панели са плоски и еднакви.

Съгласно зависима претенция 3, рефлекторите са плоски и еднакви.

Съгласно зависима претенция 4, устройствата за събиране на атмосферна вода и за съхранение на вода са еднакви.

Съгласно зависима претенция 5, реверсивният термоакмулиращ блок съдържа разтопена сол.

Съгласно зависима претенция 6, термоакмулиращият блок съдържа и силициев пясък.

Съгласно зависима претенция 7, термоакмулиращият блок съдържа и огнеупорна керамика.

Съгласно зависима претенция 8, термоакмулиращият блок съдържа и скална маса.

Съгласно зависима претенция 9, флуидно- електрическият конвертор за високо налягане включва многостепенна парна турбина.

Съгласно зависима претенция 10, флуидно- електрическият конвертор за ниско налягане включва многоцилиндров Стирлинг електрогенератор.

Съгласно зависима претенция 11, управляемият токоразпределител и интелигентният оптимизиращ управленски процесор са програмируеми.

Съгласно зависима претенция 12, първият реверсивен електропреобразовател и вторият реверсивен електропреобразовател са програмируеми.

Съгласно зависима претенция 13, интелигентният оптимизиращ управленски процесор е програмируем, включва архивна памет, оперативна памет и е конфигуриран за работа със самообучаващ се изкуствен интелект.

Съгласно зависима претенция 14, ветроелектрогенераторите са нискошумни и обезопасени, а хидрокинетични електроцентрали са с бавнооборотни аксиални подводни турбини с наклонени валове и изцяло надводни електрически и електронни компоненти и агрегати.

Задача на изобретението е да се обезпечи реверсивна термична енерго-акмулираща система за излишъците от ВЕИ с електро- парогенерация за флуидни електрогенератори, която да осигурява допълнителна първична фотоволтаична електрогенерация, чрез плоски слънчеви рефлектори и пасивно охлаждане на фотоволтаиците, да балансира електрическата мрежа чрез собствено интелигентно управление с помощта на самообучаващ се изкуствен интелект, който да обогатява работния си алгоритъм, чрез анализ на набираните ретроспективни данни и да разкрива циклични модели, от които да направи изводи, за да оптимизира непрекъснато действието на автоматично управляваната от него система.

При извършеното проучване се установи наличие на известни от предшестващото състояние на техниката документи, отразяващи нивото на техниката, които са посочени в приложения доклад от проучване, които са релевантни към обекта на проучването, а именно:

- **JP2016142272 (A)** публикуван на **08.08.2016 г.**, който разкрива система за съхраняване и разреждане на електрическа енергия, която включва система за генериране на вятърна енергия, система за генериране на слънчева топлинна енергия и електрическа мрежа, които са свързани с преобразувател на мощност. Първата система за съхранение на топлина включва първи резервоар за съхранение на топлина с ниска температура и първи резервоар за съхранение на топлина с висока температура, които са флуидно свързани. Втората система

за съхранение на топлина включва втори резервоар за съхранение на топлина с ниска температура и втори резервоар за съхранение на топлина с висока температура, които са флуидно свързани. Електрически нагревател е оперативно свързан между резервоарите за съхранение на топлина. Устройството за регулиране на електрическата мощност регулира част от излишната електрическа енергия на захранването, за да го подаде към електрическия нагревател и цикъла на термopомпата.

- **CN104734323 (A)** публикуван на **24.06.2015 г.**, който разкрива хибридна система за електрозахранване, метод за нейното захранване и електрическо оборудване включваща масив от слънчеви клетки свързана към усилвателна верига с вход, DC шина, свързана към изхода на бустерна верига и преобразователна верига, свързана към DC шината. Преобразователната верига има трифазно захранващо устройство с пълнен мост. Инверторен вход е свързан към DC шина, а двигател е свързан към изхода на инвертора. Освен това преобразователната верига е двупосочна преобразователна верига и хибридна захранваща система допълнително включва: първи контролер, свързан към преобразователната верига за управление на преобразователната верига и втори контролер, свързан към усилващата верига за регулиране на изходната мощност на масива от слънчеви клетки чрез управление на усилващата верига.

- **BG113495 (A)** публикуван на **15.09.2023 г.**, който разкрива мултисинергетична термо -фотоволтаична система, получаваща едновременно излъчване от директна и отразена светлина и използвана за нагряване на течности и генериране на електричество за захранване на термopомпи, включваща термо-фотоволтаичен модул, флуиден резервоар и електрически акумулатор. Фотоволтаичен панел е плътно монтиран върху течен радиатор и както панелът, така и радиаторът са фиксирани в обща рамка, която носи подвижно монтиран плосък рефлектор. Първи вход на оптимизирания модул е свързан към комбиниран сензор за температура на въздуха и слънчева радиация, втори сигнален вход на оптимизирания модул е свързан към комбиниран сензор, който улавя температурата и налягане в резервоара за течност, а третият сигнален вход на оптимизирания блок е свързан към комбиниран сензор, който улавя електрическите параметри на акумулатора на електрическа енергия, при което неговите работни клеми са свързани към циркулационна помпа и регулаторна помпа, към управляем контролер за зареждане и към контролен вход на електрическия преобразовател.

- **ES2385894 (A1)** публикуван на **02.08.2012 г.**, който разкрива термо-фотоволтаична електроцентрала с комбиниран цикъл, включва фотоволтаични слънчеви панели с двоен ефект и парк от слънчеви топлинни панели, за производство на електричество, както и за отопление на вода или течна топлина, така че в допълнение към електричеството, произведено от парка от слънчеви фотоволтаични панели с двоен ефект се получава вода или гореща топлопреносна течност, която след извършване на нейната терморегулация с помощта на управляваща верига и нейното съхранение в резервоар, преминава през управляваща верига преди да достигне парка на слънчеви топлинни панели, от които се получава по- голямо нагряване на тази вода или течна топлина, за по-късното ѝ приложение в електроцентралата на комбинирано цикъл на когенерация с воден парен котел и/или газ, след преминаване през парен котел.

Извършеният съпоставителен анализ между предмета от настоящото проучване и намерените при направеното проучване документи установи, следното:

НОВОСТ

В нито един от намерените при проучването документи не е разкрита реверсивна термична енерго-акумулираща система за излишъците от ВЕИ с електро-парогенерация за флуидни електрогенератори, която да съдържа всички технически признаци на обекта на проучването.

Следователно, обектът на проучването **отговаря на изискванията за новост, съгласно чл. 8 от Закона за патентите и регистрацията на полезните модели (ЗПРПМ).**

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Главен експерт ДЕЗИПМПД



Espacenet

JP2016142272A SYSTEM FOR STORING AND DISCHARGING ELECTRIC ENERGY

Applicants: GENERAL ELECTRIC TECHNOLOGY GMBH

Inventors: VIPLUV AGA, ENRICO CONTE

Classifications:

IPC **F01K25/10; F01K3/02; F01K7/32; F03G6/00; F25B1/00; F25B27/00; F28D20/00; H02J15/00; H02J3/28;**

CPC **F01K17/04 (CN); F01K23/04 (EP,US); F01K3/12 (EP,US); F01K3/18 (EP,US); F01K7/18 (CN); F03G6/00 (EP); F03G6/06 (EP); F03G6/068 (US); F03G6/071 (US); F03G6/092 (US); F22B1/16 (CN); F24H7/002 (CN); F25B17/10 (CN); F25B30/00 (US); F28D20/00 (US); F28D2020/0004 (US); Y02E10/46 (EP,US); Y02E60/14 (EP);**

Priorities: EP15153755A 2015-02-04

Application: JP2016019806A 2016-02-04

Publication: JP2016142272A 2016-08-08

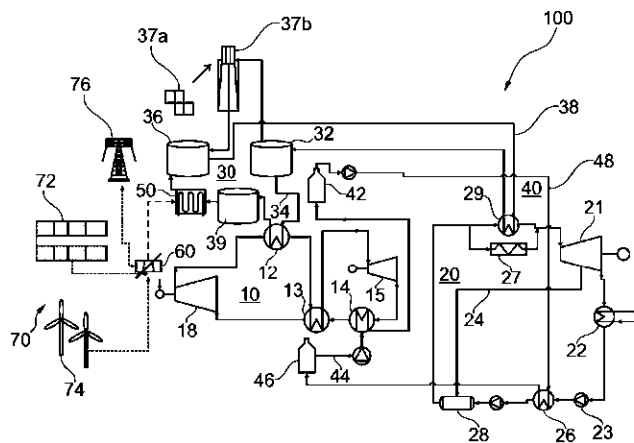
Published as: **CN105890221A; DK3054155T3; EP3054155A1; EP3054155B1; ES2655713T3; HUE035373T2; JP2016142272A; JP6696785B2; MA38821A1; MA38821B1; PL3054155T3; PT3054155T; TN2016000008A1; US2016222830A1; US9951979B2**

SYSTEM FOR STORING AND DISCHARGING ELECTRIC ENERGY

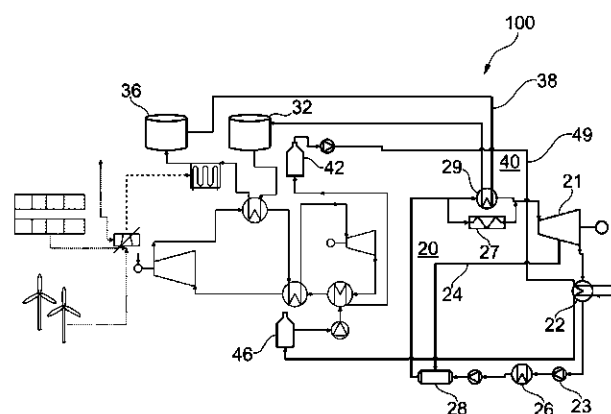
Abstract

PROBLEM TO BE SOLVED: To improve a system for storing and discharging electric energy which stores energy under utilization of heat fluid. **SOLUTION:** A system for storing and discharging electric energy which stores electric energy as thermal energy includes a heat pump cycle including a first working fluid; a water steam cycle including a second working fluid; a first heat storage system including a first thermal fluid; a second heat storage system including a second thermal fluid; an electric heater; and an electrical power adjustment device, and these elements are fluidically connected to each other. The first heat storage system includes a first low temperature heat storage tank and a first high temperature heat storage tank which are fluidically connected. The second heat storage system includes a second low temperature heat storage tank and a second high temperature heat storage tank which are fluidically connected. The electric heater is operatively connected between the heat storage tanks. The electrical power adjustment device adjusts a part of excessive electric energy of a power supply to supply it to the electric heater and the heat pump cycle. **SELECTED DRAWING:** Figure 1

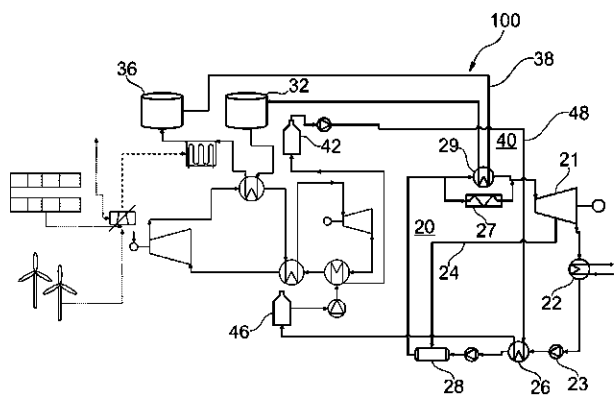
【図 2】



【 図 3 c 】



【 図 3 b 】





Espacenet

CN104734323A Hybrid power supply system, power supply method thereof and electrical equipment

Applicants: ZHUHAI GREE ELEC APPLIANCES

Inventors: CHEN HONGTAO,ZHANG KAIQIANG,SUN FENGTAO,LI HUI,CHEN XING

Classifications:

IPC **H02J7/35;**

CPC **H02J7/35 (CN); H02S40/00 (CN);** Y02E10/50 (EP);

Priorities: CN201310726787A 2013-12-24; CN201410196958A 2014-05-09

Application: CN201410196958A·2014-05-09

Publication: CN104734323A·2015-06-24

Published as: CN104734323A;**CN104734323B; CN204068407U**

Hybrid power supply system, power supply method thereof and electrical equipment

Abstract

The invention discloses a hybrid power supply system, a power supply method thereof and electrical equipment. The hybrid power supply system comprises a solar cell array, a boosted circuit, a DC bus, a converter circuit, an inverter and a motor, wherein the input end of the boosted circuit is connected with the solar cell array, the DC bus is connected with the output end of the boosted circuit, the converter circuit is connected with the DC bus and is connected with a three-phase AC supply, the converter circuit is provided with a three-phase full-bridge power device, the input end of the inverter is connected with the DC bus, and the motor is connected with the output end of the inverter. By the adoption of the hybrid power supply system, the power supply method thereof and the electrical equipment, the problem of the prior art that a hybrid power supply system is only adaptable to a single power supply is solved, and then the hybrid power supply system can be applied on more occasions.

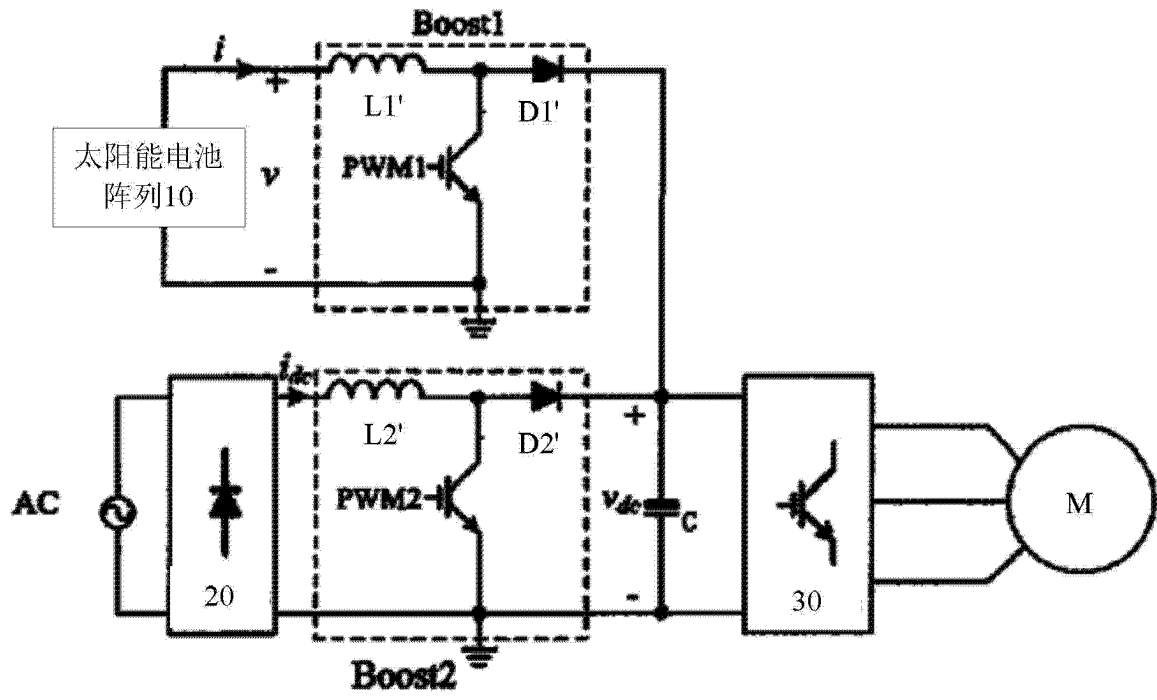


图 1

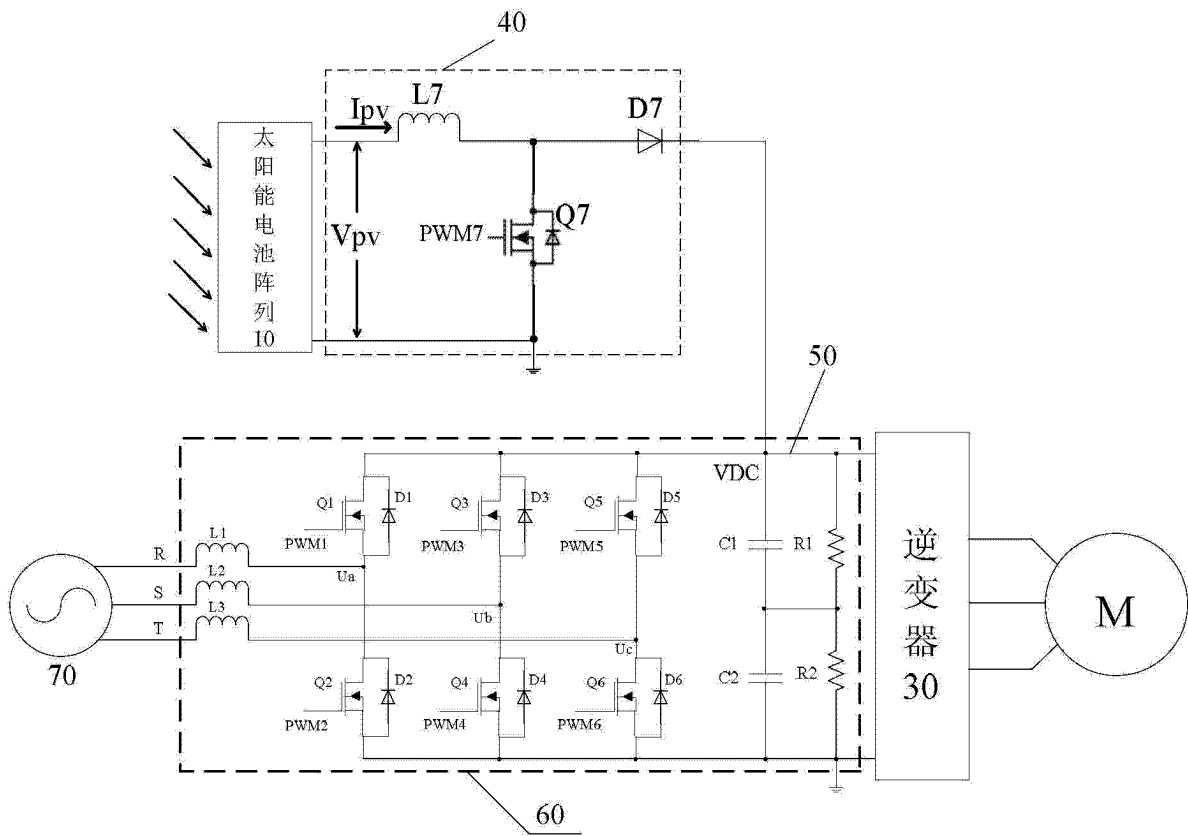


图 2



Espacenet

ES2385894A1 Combined cycle thermo-photovoltaic electrical center. (Machine-translation by Google Translate, not legally binding)

Applicants: BONONATO CLAVERO DIEGO ANGEL [ES]

Inventors: BONONATO CLAVERO DIEGO ANGEL [ES]

Classifications:

IPC **F03G6/00; H02S10/10;**

CPC **F03G6/001 (ES); F03G6/003 (ES); H02S40/44 (ES);** Y02E10/46 (EP); Y02E10/50 (EP); Y02E10/60 (EP);

Priorities: ES201030425A 2010-03-23

Application: ES201030425A·2010-03-23

Publication: ES2385894A1·2012-08-02

Published as: ES2385894A1;**ES2385894B1**

Combined cycle thermo-photovoltaic electrical center. (Machine-translation by Google Translate, not legally binding)

Abstract

Thermo-photovoltaic combined cycle power plant. The power plant is based on the combined use of a park of double-effect photovoltaic solar panels (10) and a park of solar thermal panels (11), to produce electricity as well as water heating or liquid heat, corresponding to the panels of the park (10) to that described in the invention patent 200701042 and the solar panels of the park (11) to that described in the invention patent 200801521, so that in addition to the electricity produced by the park of solar photovoltaic panels of double effect (10), water or hot heat transfer liquid is obtained that after carrying out its thermoregulation by means of a control circuit (13) and its storage in a tank (16), is passed through a control circuit (17) before reaching the park of solar thermal panels (11), from which a greater heating of this water or liquid heat is obtained, for its later application to the power plant (19) of combined cycle cogeneration with water steam boiler and/or gas, after passing through a steam boiler (21). (Machine-translation by Google Translate, not legally binding)

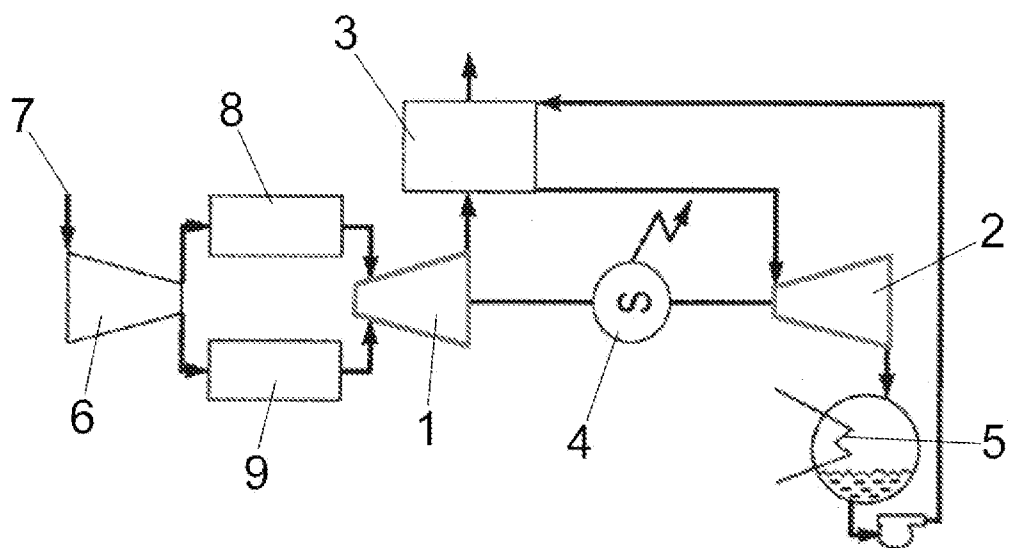


FIG. 1

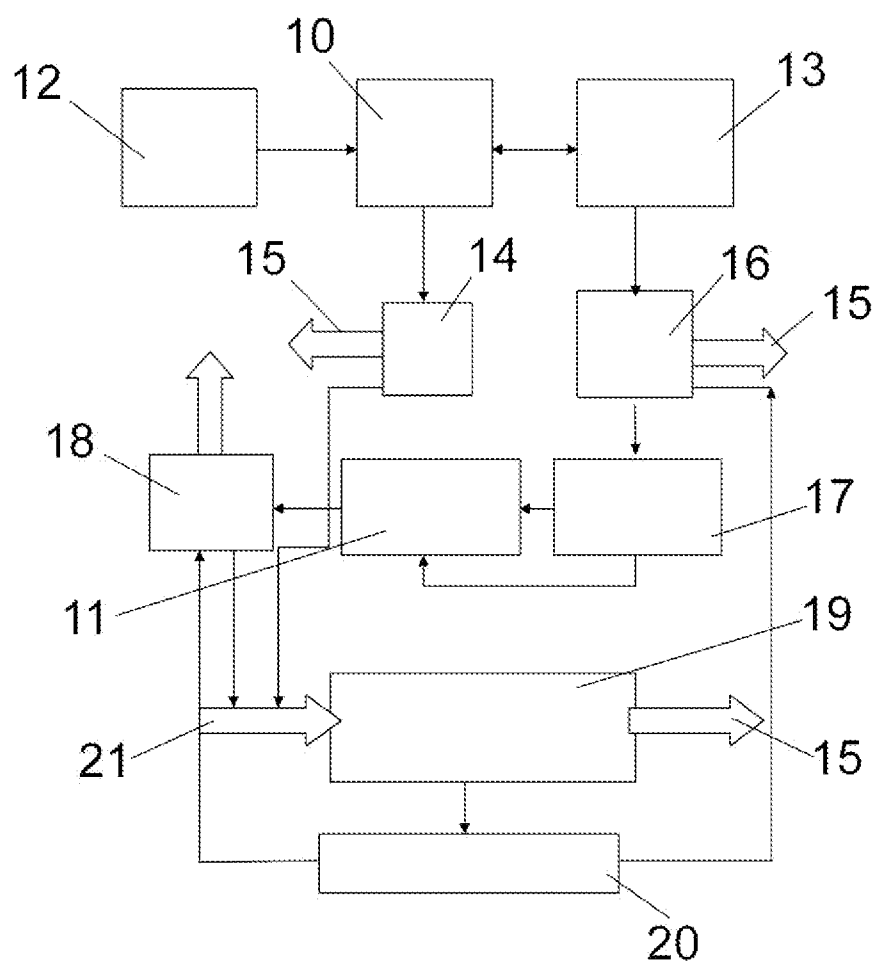


FIG. 2



US 20150280281A1

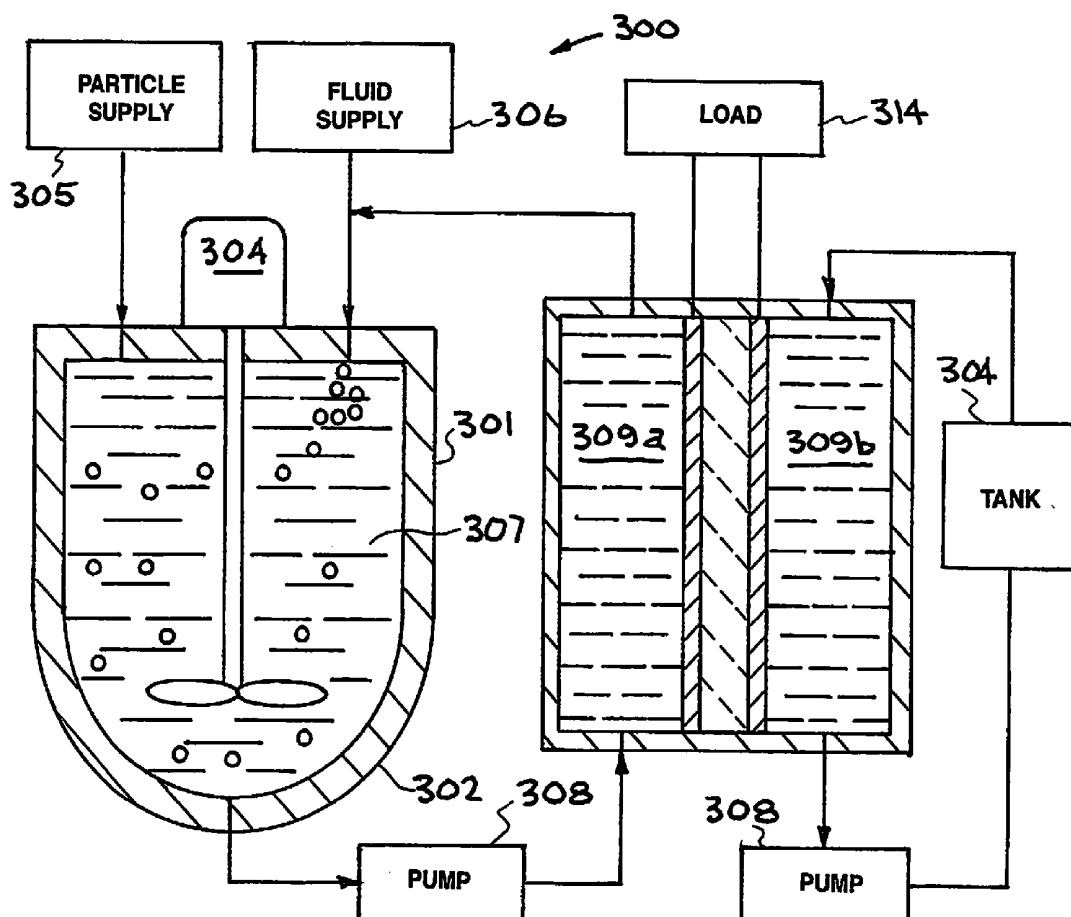
(19) **United States**(12) **Patent Application Publication**
Farmer(10) **Pub. No.: US 2015/0280281 A1**(43) **Pub. Date: Oct. 1, 2015**(54) **ELECTROCHEMICAL NANOFLUID OR
PARTICLE SUSPENSION ENERGY
CONVERSION AND STORAGE DEVICE**(52) **U.S. Cl.**
CPC *H01M 10/0561* (2013.01); *H01M 10/0569*
(2013.01); *H01M 10/0525* (2013.01)(71) Applicant: **LAWRENCE LIVERMORE
NATIONAL SECURITY, LLC.,**
Livermore, CA (US)(57) **ABSTRACT**(72) Inventor: **Joseph C. Farmer**, Tracy, CA (US)(21) Appl. No.: **14/737,754**(22) Filed: **Jun. 12, 2015****Related U.S. Application Data**

(62) Division of application No. 12/777,943, filed on May 11, 2010.

(60) Provisional application No. 61/177,520, filed on May 12, 2009.

Publication Classification(51) **Int. Cl.**
H01M 10/0561 (2006.01)
H01M 10/0525 (2006.01)
H01M 10/0569 (2006.01)

An electro-chemical energy conversion and storage device includes an enclosure, a first electrode operatively connected to the enclosure, a second electrode operatively connected to the enclosure, a nanofluid or particle suspension in the enclosure, a heat transfer unit, and a circulation system for circulating the nanofluid or particle suspension to the heat transfer unit. The nanofluid includes nanoparticles plus a dielectric or ionic fluid. The particle suspension includes particles plus a dielectric or ionic fluid. A wide range of nanoparticles or particles can be used. For example the following nanoparticles or particles can be used: metal and metal alloy particles for anodic dissolution and thermal transport; hydrides as source of hydrogen ions; lithium and lithium alloys; intercalated graphite and carbon aerogel as Li source (anodic material); intercalated transition metal oxide as Li sink (cathodic material); and semiconductors for photovoltaic conversion in photo-electrochemical or hybrid electrochemical cell.



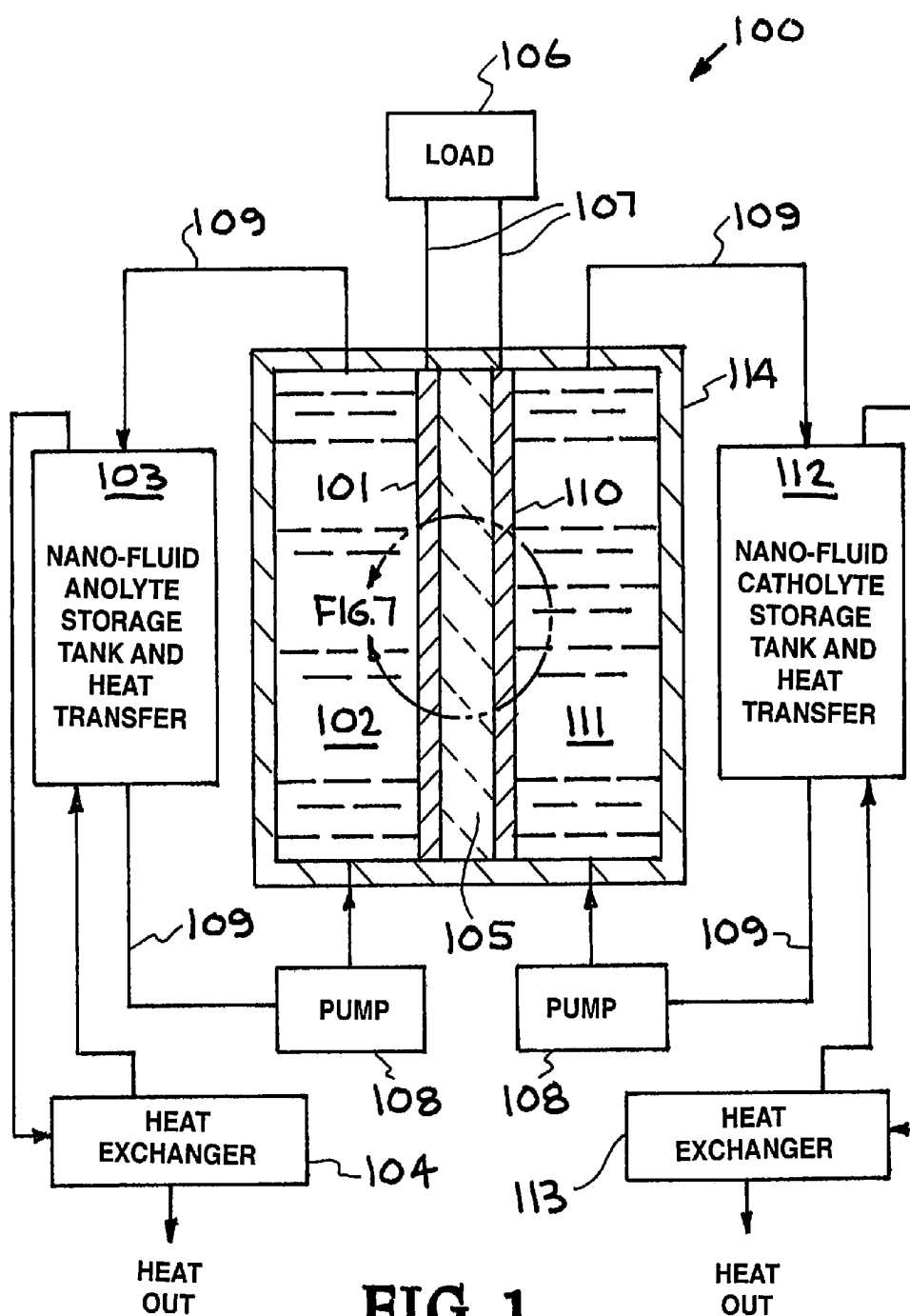


FIG. 1

FIG. 2

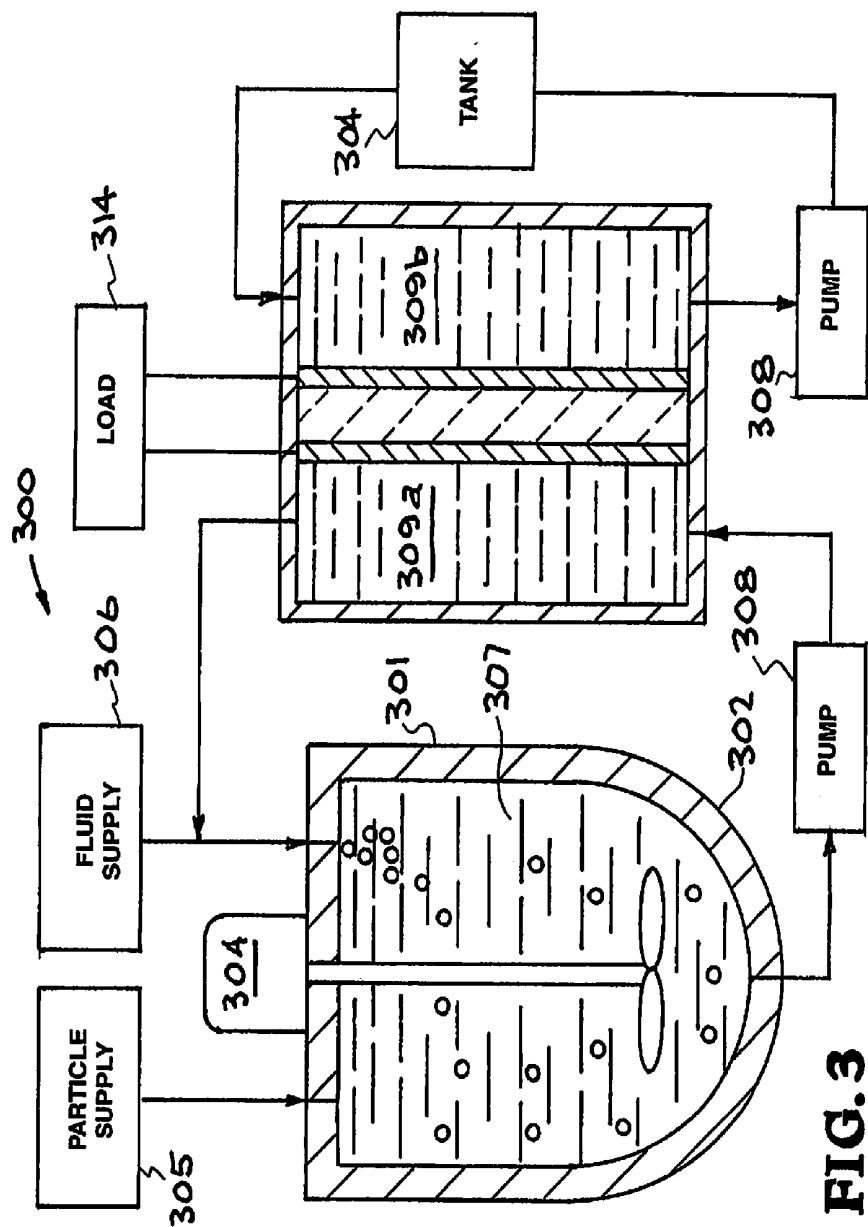


FIG. 3

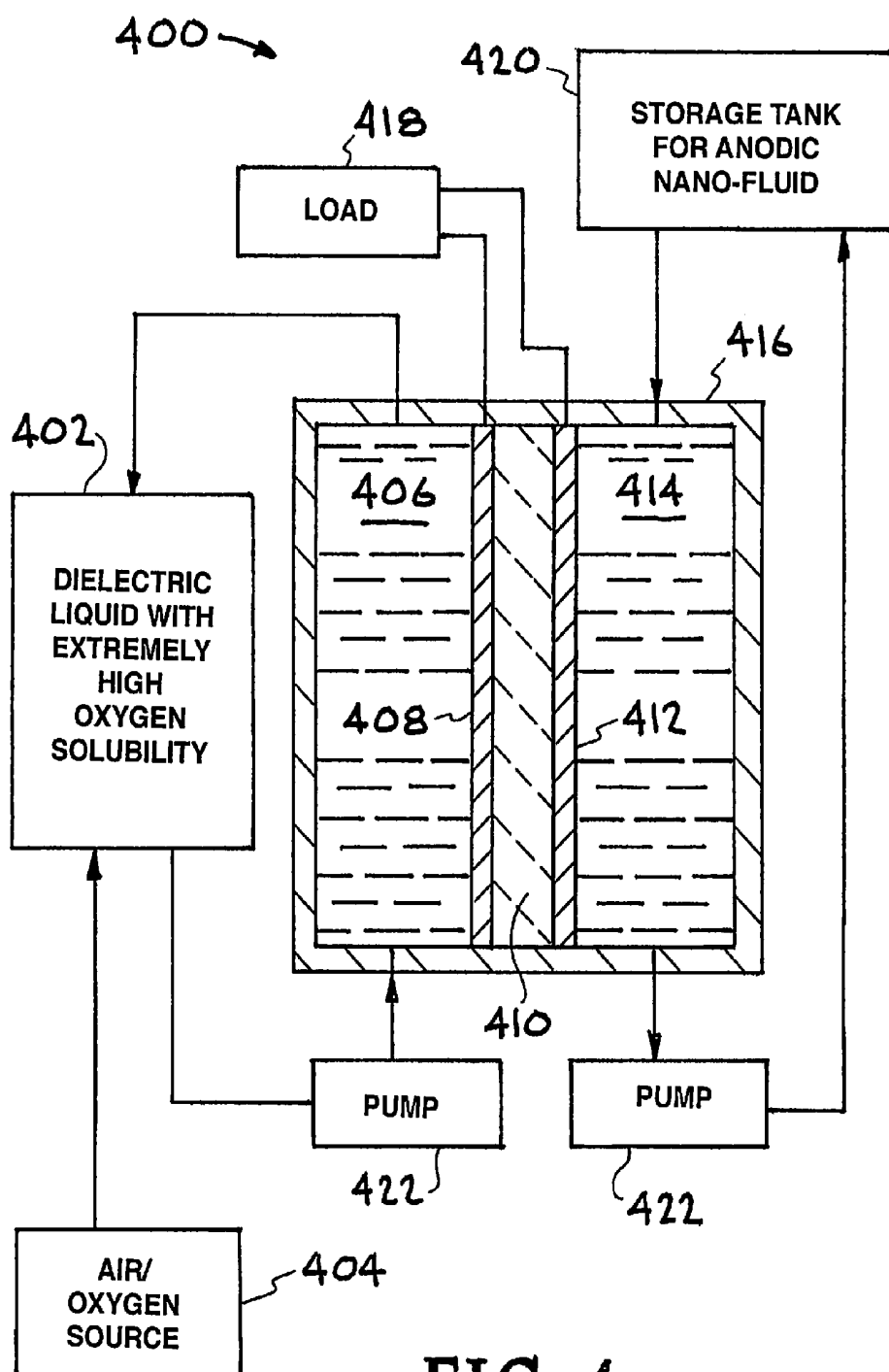


FIG. 4

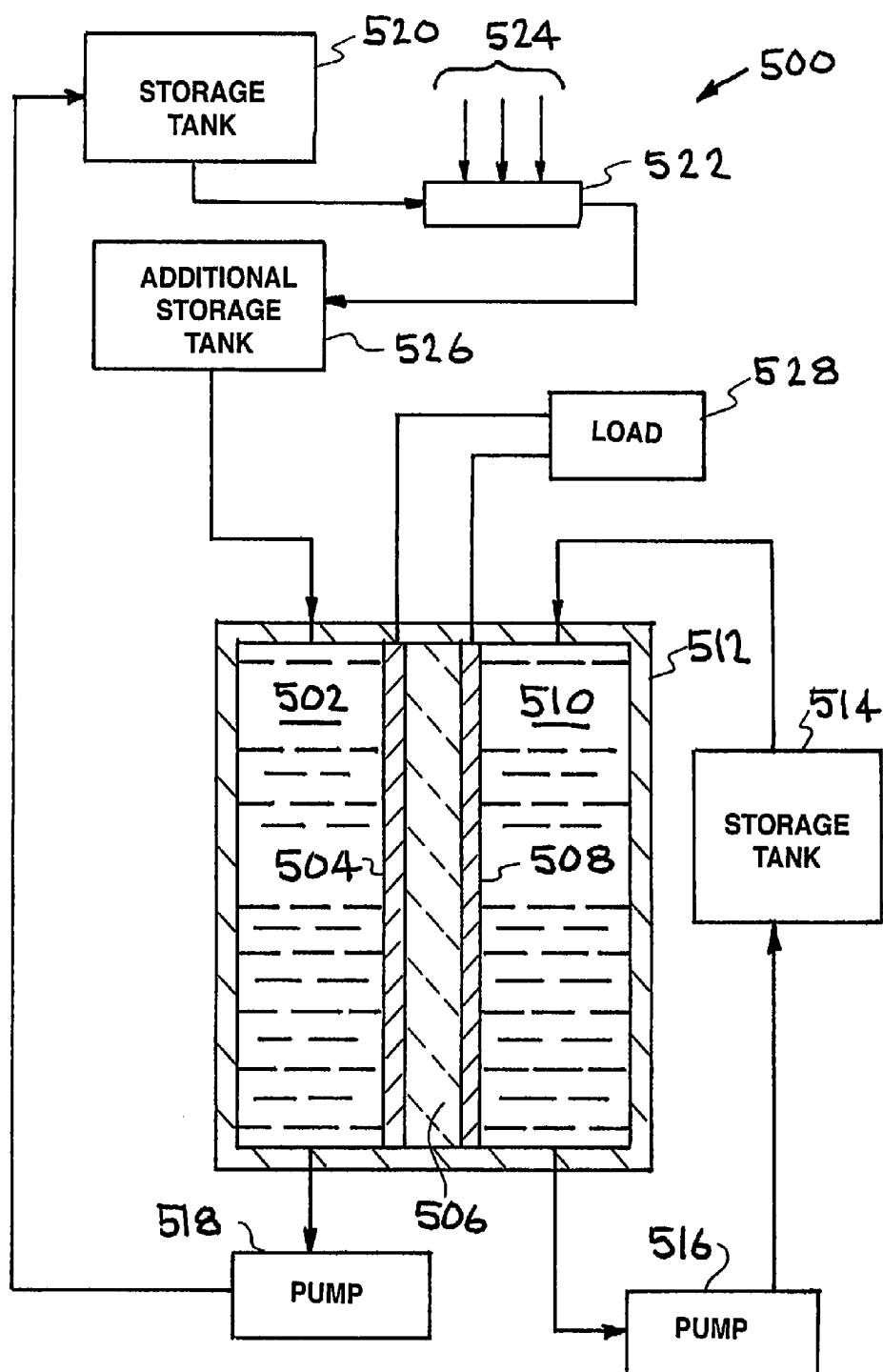


FIG. 5

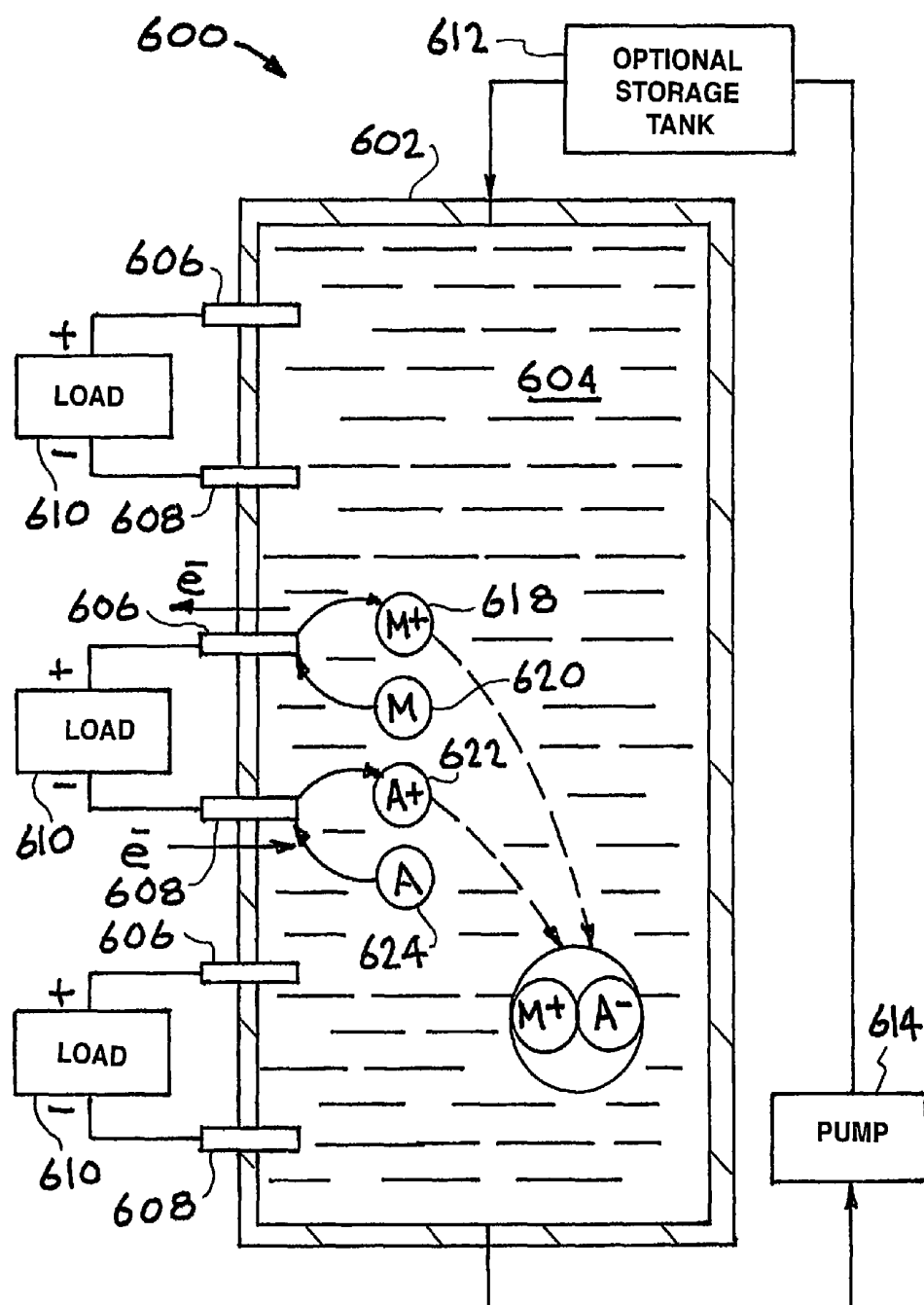


FIG. 6

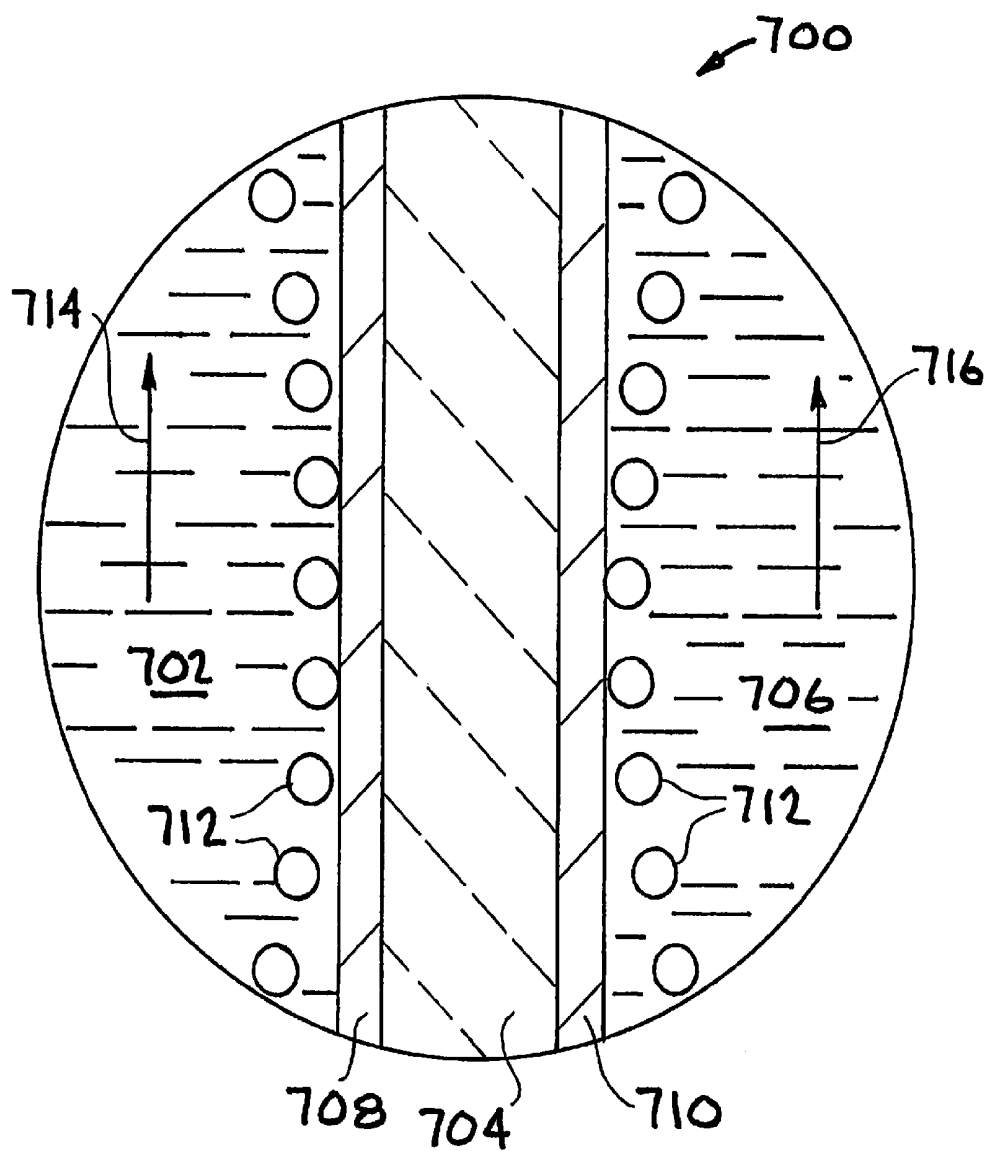


FIG. 7

ELECTROCHEMICAL NANOFLUID OR PARTICLE SUSPENSION ENERGY CONVERSION AND STORAGE DEVICE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application is a Division of patent application Ser. No. 12/777,943 filed May 11, 2010, which claims the benefit under 35 U.S.C. §119(e) of U.S. Provisional Patent Application No. 61/177,520 filed May 12, 2009 entitled "Electrochemical Nanofluid Energy Conversion and Storage Devices," the disclosure of which is hereby incorporated by reference in its entirety for all purposes.

STATEMENT AS TO RIGHTS TO INVENTIONS MADE UNDER FEDERALLY SPONSORED RESEARCH AND DEVELOPMENT

[0002] The United States Government has rights in this invention pursuant to Contract No. DE-AC52-07NA27344 between the United States Department of Energy and Lawrence Livermore National Security, LLC for the operation of Lawrence Livermore National Laboratory.

BACKGROUND

[0003] 1. Field of Endeavor

[0004] The present invention relates to energy and more particularly to electrochemical energy storage.

[0005] 2. State of Technology

[0006] Electrochemical energy storage is required for grid storage, wireless communications, portable computing, and will be essential for the realization of future fleets of electric and hybrid electric vehicles, which are now believed to be an essential part of the world's strategy for reducing our dependence on oil, and minimizing the impact of gaseous emissions of CO₂ on global warming. In looking at those possible materials that can be used for anodes in electrochemical energy conversion and storage systems, hydrogen and lithium have the highest specific capacities (Ah/kg). Hydrogen is of course used to power fuel cells, while lithium is used in advanced rechargeable batteries.

[0007] Most state of the art energy storage systems use lithium ion battery chemistry, with graphite anodes that intercalate lithium upon charging, mixed transition metal oxide cathodes that intercalate lithium during discharge, a microporous polyethylene electrode separator, and electrolyte formed from a dielectric mixed solvent composed of organic carbonates and high-mobility lithium salts. The movement of the lithium ions between the intercalation anodes and cathodes during charge and discharge is known as the "rocking chair" mechanism.

[0008] Cells with liquid electrolytes are usually contained in cylindrical or prismatic metal cans, with stack pressure maintained by the walls of the can, while cells with polymer gel electrolytes are usually contained in soft-side aluminum-laminate packages, with stack pressure achieved through thermal lamination of the electrodes and separators, thereby forming a monolithic structure.

[0009] The active graphite or transition metal oxide materials used in the electrodes exist as fine powders, coated onto thin metal foils of copper and aluminum, respectively, and held in place by a PVDF binder. Both natural and manmade graphite such as MCMB have been used for the anodes, while Li_xCoO₂, LiNiO₂, LiMn₂O₄, mixed transition metal oxides

with cobalt, nickel and manganese, and iron-phosphates are common choices for the cathode.

[0010] Over the past decade, these systems have attained outstanding specific energy and energy density, exceptional cycle life and rate capabilities that enable them to now be considered for both vehicular and power tool applications, in addition to their early applications in wireless communications and portable computing. The best commercially available, polymer-gel lithium ion battery now has a specific energy of 180 to 200 Wh/kg, an energy density of 360 to 400 Wh/L, and a reasonably good rate capability, allowing discharge at C/2 or better.

[0011] Both liquid prismatic and polymer gel cells have been incorporated into large high-capacity power packs and used to power the mobile electric vehicles. Such high capacity systems have state-of-the-art computerized charge and discharge control, which includes graphical user interfaces, sensing for monitoring the health of individual cells, and charge balancing networks.

[0012] Such lithium ion batteries, which rely on the rocking chair mechanism, are generally believed to be safer than those where lithium exists in the reduced metallic state. However, the use of flammable liquid-phase and two-phase polymer gel electrolytes, coupled with a high energy density, a relatively delicate 20-micron thick polymeric separator, and the possibility of lithium plating and dendrite formation due to non-uniform stack pressure and electrode misalignment has led to safety problems with these energy storage systems. The possibility of such an event occurring on commercial airliners, where many passengers carry laptop computers and cell phones with such batteries, is especially disconcerting. These events have occurred on much larger scale, and have caused industry-wide concern in the continued use of this important technology.

[0013] Adequate and intelligent thermal management in these cells is essential. High rates of charge or discharge drives the temperature upward due to resistive heating of the electrolyte. When the core temperature of these cells exceeds approximately 150° F., the systems frequently become unstable, with the possible initiation of autocatalytic reactions, which can lead to thermal runaway and catastrophic results. Disproportionation of the transition metal oxides can liberate sufficient oxygen to support oxidation of the organic carbonate solvents used in the liquid or polymer-gel electrolytes. It is now recognized that while conventional systems provide high energy density, their safety remains problematic.

[0014] The treatise, *Introduction to Nanotechnology*, by Charles P. Poole, Jr., and Frank J. Owens. John Wiley & Sons, 2003, states: "Nanotechnology is based on the recognition that particles less than the size of 100 nanometers (a nanometer is a billionth of a meter) impart to nanostructures built from them new properties and behavior. This happens because particles which are smaller than the characteristic lengths associated with particular phenomena often display new chemistry and physics, leading to new behavior which depends on the size. So, for example, the electronic structure, conductivity, reactivity, melting temperature, and mechanical properties have all been observed to change when particles become smaller than a critical size."

SUMMARY

[0015] Features and advantages of the present invention will become apparent from the following description. Appli-

cants are providing this description, which includes drawings and examples of specific embodiments, to give a broad representation of the invention. Various changes and modifications within the spirit and scope of the invention will become apparent to those skilled in the art from this description and by practice of the invention. The scope of the invention is not intended to be limited to the particular forms disclosed and the invention covers all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the claims.

[0016] The present invention provides an electro-chemical energy conversion and storage device. The electro-chemical energy conversion and storage device includes an enclosure, a first electrode operatively connected to the enclosure, a second electrode operatively connected to the enclosure, a nanofluid or particle suspension in the enclosure, a heat transfer unit, and a circulation system for circulating the nanofluid or particle suspension to the heat transfer unit.

[0017] The nanofluid is defined as: nanofluid=nanoparticles+dielectric or ionic fluid. A wide range of nanoparticles can be used. For example the following nanoparticles can be used: metal and metal alloy particles for anodic dissolution and thermal transport; hydrides as source of hydrogen ions; lithium and lithium alloys; intercalated graphite and carbon aerogel as Li source (anodic material); intercalated transition metal oxide as Li sink (cathodic material); and semiconductors for photovoltaic conversion in photo-electrochemical or hybrid electrochemical cell.

[0018] The particle suspension is defined as: particle suspension=particles+dielectric or ionic fluid. A wide range of particles can be used. For example the following particles can be used: metal and metal alloy particles for anodic dissolution and thermal transport; hydrides as source of hydrogen ions; lithium and lithium alloys; graphite intercalated with lithium; and carbon aerogel with a coating of lithium as a lithium source (anodic material); intercalated transition metal oxides as lithium sink (cathodic material); and semiconductors for photovoltaic conversion in photo-electrochemical or hybrid electrochemical cell.

[0019] Nanoparticles or particles for the nanofluid or particle suspension anolyte can be made of pure elemental materials including Pb, Cd, Zn, Fe, Na, Ca, Mg, Al, and Li, as well as any alloy formed from these pure elemental materials. In the case of a nanofluid flow cell using lithium-ion type chemistry, the nanoparticles in the anolyte could be Li-intercalated natural graphite, Li-intercalated synthetic graphite, Li—S; alloys, Li—Sn alloys, or other Li-containing alloys or compounds. Similar compositions can be used for particles suspensions. In the case of a nanofluid flow cell using lithium-ion type chemistry, the nanoparticles in the catholyte could be a transition metal oxide such as Li_xCoO_2 , Li_xNiO_2 , $\text{Li}_x\text{Mn}_2\text{O}_4$, a mixed transition metal oxide such as $\text{Li}_x(\text{Co}, \text{Ni}, \text{Mn})\text{O}_2$, or a phosphate such as Li_xFePO_4 . Similar compositions can be used for particle suspensions. Hydrides can also be used for anolyte nanoparticles or particles.

[0020] The present invention can be incorporated in different electrochemical and photo-electrochemical cell configurations. For example, present invention can be incorporated in the following cell configurations: anodic and cathodic nanofluid or particle suspension or particle suspensions in both compartments of divided cell (anodic nanofluid or particle suspension in the anode compartment of the cell and cathodic nanofluid or particle suspension in the cathode compartment of the cell); anodic nanofluid or particle suspension in the

anode compartment for air or oxygen breathing cell; a storage system for oxygen/peroxide in oxygen/peroxide depolarized system; an air-sparged nanofluid or particle suspension oxygen cathode for air breathing cell; an electrolyte nanofluid or particle suspension in cell with solid anode and cathode; a photovoltaic nanofluid or particle suspension in photo-electrochemical cell; and anodic and cathodic nanoparticles forming a single nanofluid or particle suspension, with localized anode and cathode sites for energy harvesting from particles.

[0021] Some of the advantages of the present invention include: enhanced thermal management; thereby preventing thermal runaway in high capacity systems; overcoming solubility limit encountered in conventional liquid redox flow batteries through the use of solid particles; ability to provide unlimited capacity for a wide variety of chemistries; by simply enlarging the storage volumes for nanofluids or particle suspensions; fast mechanical recharging; and extremely high charge and discharge rates for vehicular applications (extreme rate capability), enabled by the short diffusion length, coupled with flow-control of turbulence and mixing.

[0022] Uses of the present invention include load leveling, uninterruptable power for computing and telecommunications, electric vehicles, hybrid electric vehicles, and other uses.

[0023] The invention is susceptible to modifications and alternative forms. Specific embodiments are shown by way of example. It is to be understood that the invention is not limited to the particular forms disclosed. The invention covers all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0024] The accompanying drawings, which are incorporated into and constitute a part of the specification, illustrate specific embodiments of the invention and, together with the general description of the invention given above, and the detailed description of the specific embodiments, serve to explain the principles of the invention.

[0025] FIG. 1 illustrates a divided energy storage battery with anodic and cathodic nanofluid or particle suspension or particle suspensions in both compartments of the divided battery.

[0026] FIG. 2 illustrates an air or oxygen breathing nanofluid or particle suspension flow battery.

[0027] FIG. 3 illustrates a circulation system for a nanofluid or particle suspension.

[0028] FIG. 4 illustrates an air-sparged nanofluid or particle suspension oxygen cathode for air breathing cell.

[0029] FIG. 5 illustrates a photovoltaic nanofluid or particle suspension in photo-electrochemical cell.

[0030] FIG. 6 illustrates an anodic and cathodic nanoparticles forming a single nanofluid or particle suspension, with localized anode and cathode sites for energy harvesting from particles

[0031] FIG. 7 is the area designated in FIG. 1 that illustrates the nanofluid or particle suspension.

DETAILED DESCRIPTION OF SPECIFIC EMBODIMENTS

[0032] Referring to the drawings, to the following detailed description, and to incorporated materials, detailed information about the invention is provided including the description

of specific embodiments. The detailed description serves to explain the principles of the invention. The invention is susceptible to modifications and alternative forms. The invention is not limited to the particular forms disclosed. The invention covers all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the claims.

[0033] Electrochemical energy storage is required for numerous applications which are now believed to be an essential part of the world's strategy for reducing our dependence on oil, and minimizing the impact of gaseous emissions of CO₂ on global warming. Cells with liquid electrolytes are usually contained in cylindrical or prismatic metal cans, with stack pressure maintained by the walls of the can, while the two-phase polymer gel electrolytes are usually contained in an aluminum-laminate "candy wrapper" pouch, with stack pressure achieved through thermal lamination of the electrodes and separators, thereby forming a monolithic structure. Over the past decade, these systems have attained outstanding specific energy and energy density, exceptional cycle life and rate capabilities that enable them to now be considered for both vehicular and power tool applications, in addition to their early applications in wireless communications and portable computing. The best commercially available, polymer-gel lithium ion battery now has a specific energy of 180 to 200 Wh/kg, an energy density of 350 to 400 Wh/L, and a reasonably good rate capability, allowing discharge at C/2. A typical solid polymer electrolyte (SPE) cell has a specific energy of only ~100 Wh/kg, and an energy density of only ~80 Wh/L (though some higher values have been sporadically reported). Such lithium ion batteries, which rely on the rocking chair mechanism, are generally believed to be safer than those where lithium exists in the reduced metallic state. However, the use of flammable liquid-phase and two-phase polymer gel electrolytes, coupled with a high energy density, a relatively delicate 20-micron thick polymeric separator, and the possibility of lithium plating and dendrite formation due to non-uniform stack pressure and electrode misalignment has led to safety problems with these energy storage systems. Adequate and intelligent thermal management in these cells is essential. High rates of charge or discharge drives the temperature upward due to resistive heating of the electrolyte. When the core temperature of these cells exceeds approximately 150° F., the systems frequently become unstable, with the possible initiation of autocatalytic reactions, which can lead to thermal runaway and catastrophic results. Disproportionation of the transition metal oxides can liberate sufficient oxygen to support oxidation of the organic carbonate solvents used in the liquid or polymer-gel electrolytes. It is now recognized that while conventional systems provide high energy density, their safety remains problematic.

[0034] The present invention provides an electro-chemical energy conversion and storage device. The electro-chemical energy conversion and storage device includes an enclosure, a first electrode operatively connected to the enclosure, a second electrode operatively connected to the enclosure, a nanofluid or particle suspension in the enclosure, a heat transfer unit, and a circulation system for circulating the nanofluid or particle suspension to the heat transfer unit.

[0035] The nanofluid is defined as: nanofluid=nanoparticles+dielectric or ionic fluid. A wide range of nanoparticles can be used. For example the following nanoparticles can be used: metal and metal alloy particles for anodic dissolution and thermal transport; hydrides as source

of hydrogen ions; lithium and lithium alloys; intercalated graphite and carbon aerogel as Li source (anodic material); intercalated transition metal oxide as Li sink (cathodic material); and semiconductors for photovoltaic conversion in photo-electrochemical or hybrid electrochemical cell.

[0036] The particle suspension is defined as: particle suspension=particles+dielectric or ionic fluid. A wide range of particles can be used. For example the following particles can be used: metal and metal alloy particles for anodic dissolution and thermal transport; hydrides as source of hydrogen ions; lithium and lithium alloys; intercalated graphite and carbon aerogel as Li source (anodic material); intercalated transition metal oxide as Li sink (cathodic material); and semiconductors for photovoltaic conversion in photo-electrochemical or hybrid electrochemical cell.

[0037] Examples of nanoparticles and particles that can be used in the nanofluid or particle suspension are included in Table 1 below.

TABLE 1

Anodic Metal Nanoparticles	Li Ion Type Nanoparticles	Anodic Hydride Nanoparticles
Pb & Pb Alloys	Lithium and Lithium Alloys	LaCuNi ₄
Cd & Cd Alloys	Graphite Intercalated with Li	Mm0.85Ce0.15Ni ₅
Zn & Zn Alloys	Intercalation Cathode for Li-Ion Type Fluid Cell	LaNi ₅
Fe & Fe Alloys		La _{0.7} Ce _{0.3} Ni ₅
Si & Si Alloys		FeTi
Na & Na Alloys		Niobium
Ca & Ca Alloys		Mm1.05Ni _{4.97} Al _{0.03}
Mg & Mg Alloys		FeTiMn
Al & Al Alloys		Aluminate
Li & Li Alloys		
Ag & Ag Alloys		
Cu & Cu Alloys		

Examples of Nanoparticles for Nanofluid or Particle Suspension

[0038] Examples of electro-chemical energy conversion and storage systems constructed in accordance with the present invention are described below.

Example 1

Divided Energy Storage Battery

[0039] An example of electro-chemical energy conversion and storage systems constructed in accordance with the present invention is illustrated in FIG. 1. A divided energy storage battery with anodic and cathodic nanofluid or particle suspension or particle suspensions in both compartments of the divided battery is shown in FIG. 1. The divided energy storage battery is designated generally by the reference numeral 100. The divided energy storage battery 100 provides a new inherently safe, high-energy, high-rate rechargeable battery. The divided energy storage battery 100 includes the following components: electro-catalytic anode 101, nanofluid or particle suspension anolyte 102, nanofluid or particle suspension anolyte storage tank & heat transfer 103, heat rejection—anode 104, electrolyte & separator 105, load 106, electrical connectors 107, pump 108, fluid lines 109, electro-catalytic cathode 110, nanofluid or particle suspension catholyte 111, nanofluid or particle suspension catholyte storage tank & heat transfer 112, heat rejection—cathode

113, and housing 114. The housing is made at least in part of a non-conductive material. The electrolyte & separator 105 is constructed of solid state electrolytes for electrode separator-electrolyte layer. Examples of the solid state electrolytes for electrode separator-electrolyte layer are shown in Table 2 below.

TABLE 2

Electrolyte	Conductivity (S m ⁻¹)
AgI	10 ⁻³
Ag ₃ SI	1
RbAg ₄ I ₅	3.0
β-(Al ₂ O ₃) ₁₁ (Na ₂ O) ₁	3
LiI(Al ₂ O ₃)	10 ⁻³
LiI	10 ⁻⁵
LiX-PEO	10 ⁻⁵
Li _{0.35} I _{0.14} O _{0.007} P _{0.11} S _{0.98}	5 × 10 ⁻²
MEEP	10 ⁻²
Plasticized SPEs	10 ⁻¹
Li _{0.35} I _{0.12} O _{0.31} P _{0.12} S _{0.58}	2 × 10 ⁻³
Li _{0.39} N _{0.020} O _{3.47} P _{0.12}	3 × 10 ⁻⁴

[0040] The electro-catalytic anode 101 gives up electrons at a potential above that of the electro-catalytic cathode 110. The conductive link via the load 106 through electrical connectors 107 carries electrons from the electro-catalytic anode 101 to the electro-catalytic cathode 110. The nanofluid or particle suspension anolyte 102 dissociates ions. These ions serve to deliver electrons and chemical matter through the nanofluid or particle suspension anolyte 102 to balance the flow of electric current through the load 106 during operation.

[0041] The divided energy storage battery 100 includes electro-catalytic anode 101 and electro-catalytic cathode 110 electrically connected across load 106 by electrical connectors 107. A nanofluid or particle suspension anolyte 102 is contained within housing 114 adjacent electro-catalytic anode 101. The nanofluid or particle suspension anolyte 102 is circulated to a nanofluid or particle suspension anolyte storage tank and heat transfer unit 103 through fluid lines 109 by pump 108. Nanofluid or particle suspension anolyte storage tank and heat transfer unit 103 provides heat rejection 104. The nanofluid or particle suspension anolyte 102 is a nanofluid or particle suspension.

[0042] The nanofluid is defined as: nanofluid=nanoparticles+dielectric or ionic fluid. A wide range of nanoparticles can be used. The particle suspension is defined as: particle suspension=particles+dielectric or ionic fluid. A wide range of particles can be used. Examples of nanoparticles and particles that can be used in the nanofluid or particle suspension are included in Table 1 above.

[0043] A nanofluid or particle suspension catholyte 111 is contained within housing 114 adjacent electro-catalytic cathode 110. The nanofluid or particle suspension catholyte 111 is circulated to a nanofluid or particle suspension catholyte storage tank and heat transfer 112 through fluid lines 109 by pump 108. Nanofluid or particle suspension catholyte storage tank and heat transfer 112 provides heat rejection 113.

[0044] The electro-catalytic anode 101 gives up electrons at a potential above that of the electro-catalytic cathode 110. The conductive link via the load 106 through electrical connectors 107 carries electrons from the electro-catalytic anode 101 to the electro-catalytic cathode 110. nanofluid or particle suspension catholyte 111 dissociates ions. These ions serve to deliver electrons and chemical matter through the nanofluid

or particle suspension catholyte 111 to balance the flow of electric current through the load 106 during operation.

[0045] The nanofluid is defined as: nanofluid=nanoparticles+dielectric or ionic fluid. A wide range of nanoparticles can be used. The particle suspension is defined as: particle suspension=particles+dielectric or ionic fluid. A wide range of particles can be used. Examples of nanoparticles and particles that can be used in the nanofluid or particle suspension are included in Table 1 above.

Example 2

Air or Oxygen Breathing Battery

[0046] An example of an electro-chemical energy conversion and storage system constructed in accordance with the present invention is illustrated in FIG. 2. The air or oxygen breathing nanofluid or particle suspension flow battery is designated generally by the reference numeral 200. The air or oxygen breathing nanofluid or particle suspension flow battery 200 includes the following components: electro-catalytic anode 201, nanofluid or particle suspension anolyte 202, nanofluid or particle suspension anolyte storage tank & heat transfer 203, heat rejection 204, electrolyte & separator 205, oxygen, cathode 206, oxygen or air 207, selective transport of molecular oxygen 208, oxygen selective membrane 209, load 210, pump 211, fluid lines 212, electrical connectors 213, and housing 214. The housing is made at least in part of a non-conductive material. The air or oxygen breathing nanofluid or particle suspension flow battery 200 provides a new inherently safe, high-energy, high-rate rechargeable battery.

[0047] The air or oxygen breathing nanofluid or particle suspension flow battery 200 includes electro-oxygen cathode 206, and electro-catalytic anode 201. The electro-oxygen cathode 206 and electro-catalytic anode 201 are electrically connected across load 206 by electrical connectors 213.

[0048] Oxygen or air 207 provides selective transport of molecular oxygen 208 through oxygen selective membrane 209 to electrolyte and separator 205.

[0049] The nanofluid or particle suspension anolyte 202 is contained within housing 214 adjacent oxygen cathode 206 and electro-catalytic anode 201.

[0050] The electro-catalytic anode 201 gives up electrons at a potential above that of the electro-oxygen cathode 206. The conductive link via the load 210 through electrical connectors 213 carries electrons from the electro-catalytic anode 201 to the electro-oxygen cathode 206. The nanofluid or particle suspension anolyte 202 dissociates ions. These ions serve to deliver electrons and chemical matter through the nanofluid or particle suspension anolyte 202 to balance the flow of electric current through the load 210 during operation.

[0051] The nanofluid or particle suspension anolyte 202 is circulated to a nanofluid or particle suspension anolyte storage tank and heat transfer unit 203 through fluid lines 212 by pump 211. Nanofluid or particle suspension anolyte storage tank and heat transfer unit 203 provides heat rejection 204. The nanofluid or particle suspension anolyte 202 is a nanofluid or particle suspension.

[0052] The nanofluid is defined as: nanofluid=nanoparticles+dielectric or ionic fluid. A wide range of nanoparticles can be used. The particle suspension is defined as: particle suspension=particles+dielectric or ionic fluid. A wide range of particles can be used. Examples of nanoparticles and particles that can be used in the nanofluid or particle suspension are included in Table 1 above.

Example 3

Circulation System for Nanofluid or Particle Suspension

[0053] Referring now to FIG. 3, an example of a circulation system for a nanofluid or particle suspension energy storage system is illustrated. The circulation system is designated generally by the reference numeral 300. The circulation system 300 includes the following components: vessel 301, rounded bottom 302, motor driven agitator 304, particle supply 305, fluid supply 306, nanofluid or particle suspension solution 307, pump 308, cell 309, pump 310, tank 312, and load 314. The nanofluid or particle suspension solution 307 is a nanofluid or particle suspension.

[0054] The nanofluid or particle suspension solution 307 is produced by fluid from fluid supply 306 and particles from particle supply 305 being introduced into the vessel 301. The motor driven agitator 304 mixes fluid from fluid supply 306 and particles from particle supply 305. The nanofluid or particle suspension solution 307 is circulated to a nanofluid or particle suspension storage tank and heat transfer unit 309 through fluid lines by pump 308. A pump 310 pumps fluid from tank 312 into cell 309. The nanofluid or particle suspension solution 307 is a nanofluid or particle suspension.

[0055] The nanofluid is defined as: nanofluid=nanoparticles+dielectric or ionic fluid. The particle suspension is defined as: particle suspension=particles+dielectric or ionic fluid. The fluid in fluid supply 306 is a dielectric or ionic fluid. A wide range of nanoparticles and particles can be used. Examples of nanoparticles and particles that can be used in the nanofluid or particle suspension are included in Table 1 above.

[0056] The nanofluid or particle suspension storage tank and heat transfer unit 309 provides heat rejection. The nanofluid or particle suspension storage tank and heat transfer unit 309 includes an electro-catalytic anode, an electro-catalytic cathode, and load. The electro-catalytic anode gives up electrons at a potential above that of the electro-catalytic cathode. The conductive link via the load through electrical connectors carries electrons from the electro-catalytic anode to the electro-catalytic cathode. The nanofluid or particle suspension anolyte dissociates ions. These ions serve to deliver electrons and chemical matter through the nanofluid or particle suspension anolyte to balance the flow of electric current through the load during operation.

Example 4

Air-Sparged Nanofluid or Particle Suspension Oxygen Cathode

[0057] Referring now to FIG. 4, an example of an air-sparged nanofluid or particle suspension oxygen cathode for air breathing cell is illustrated. The air-sparged nanofluid or particle suspension oxygen cathode for air breathing cell is designated generally by the reference numeral 400.

[0058] The air-sparged nanofluid or particle suspension oxygen cathode 400 includes dielectric liquid with extremely high oxygen solubility 402, air or oxygen source 404, cathode 406, porous metal contact 408, electrode separator and electrolyte layer 410, porous metal contact 412, anode chamber with anodic nanofluid or particle suspension 414, housing 416; load 418, storage tank 420, and pump 422. The housing is made at least in part of a non-conductive material. The air

or oxygen source 404 is connected to dielectric liquid with extremely high oxygen solubility 402.

[0059] The anodic nanofluid or particle suspension 414 is circulated to a storage tank 420 through fluid lines by pump 422. Nanofluid or particle suspension anodic nanofluid or particle suspension 414 is a nanofluid or particle suspension.

[0060] The nanofluid is defined as: nanofluid=nanoparticles+dielectric or ionic fluid. A wide range of nanoparticles can be used. The particle suspension is defined as: particle suspension=particles+dielectric or ionic fluid. A wide range of particles can be used. Examples of nanoparticles and particles that can be used in the nanofluid or particle suspension are included in Table 1 above.

[0061] The cathode 406 and porous metal contact 412 transfer electrons. The conductive link via the load 418 through electrical connectors carries electrons from the cathode 406 to porous metal contact 412. The anodic nanofluid or particle suspension 414 dissociates ions. These ions serve to deliver electrons and chemical matter through the anodic nanofluid or particle suspension 414 to balance the flow of electric current through the load 418 during operation.

Example 5

Photovoltaic Nanofluid or Particle Suspension in Photo-Electrochemical Cell

[0062] Referring now to FIG. 5, an example of a photovoltaic nanofluid or particle suspension in photo-electrochemical cell is illustrated. The photovoltaic nanofluid or particle suspension in photo-electrochemical cell is designated generally by the reference numeral 500. The photovoltaic nanofluid or particle suspension in photo-electrochemical cell 500 includes the following components: photo chemically activated fluid chamber 502, porous metal contact 504, electrode separator and electrolyte layer 506, porous metal contact 508, nanofluid or particle suspension chamber 510, housing 512, storage tank, pump 516, pump 518, storage tank, 520, photo chemical reactor 522, light source 524, additional storage tank 526, and load 528.

[0063] Electrical power is produced from sun light or other light 524. The sun light or other light 524 is received by photo chemical reactor 522. The photo chemical reactor 522 is connected to additional storage tank 526, photo chemically activated fluid chamber 502, pump 518, and storage tank, 520. The sun light or other light 524 received by photo chemical reactor 522 results in photochemical reaction of nanoparticle or particle suspension in photo chemical reactor 522. The nanoparticle or particle suspension is circulated through additional storage tank 526, photo chemically activated fluid chamber 502, and storage tank, 520 by pump 518.

[0064] A porous metal contact 504 is operatively connected to the photo chemically activated fluid chamber 502. An electrode separator and electrolyte layer 506 is located between porous metal contact 504 and porous metal contact 508. The electrode separator and electrolyte layer 506 is constructed of solid state electrolytes for electrode separator-electrolyte layer. Examples of the solid state electrolytes for electrode separator-electrolyte layer are shown in Table 2 above.

[0065] Porous metal contact 504 and porous metal contact 508 are electrically connected across load 528 by electrical connectors. A nanofluid or particle suspension is contained in nanofluid or particle suspension chamber 510. The nanofluid or particle suspension is circulated through storage tank 514

and nanofluid or particle suspension chamber **510** by pump **516**. The nanofluid or particle suspension in the nanofluid or particle suspension chamber **510** can be a wide range of nanoparticles or a wide range of particles. Examples of nanoparticles and particles that can be used are included in Table 1 above.

Example 6

Anodic and Cathodic Nanoparticles Forming a Single Nanofluid or Particle Suspension, with Localized Anode and Cathode Sites for Energy Harvesting from Particles

[0066] Referring now to FIG. 6, an example of an anodic and cathodic nanoparticles forming a single nanofluid or particle suspension, with localized anode and cathode sites for energy harvesting from particles is illustrated. The anodic and cathodic nanoparticles forming a single nanofluid or particle suspension, with localized anode and cathode sites for energy harvesting from particles is designated generally by the reference numeral **600**. The anodic and cathodic nanoparticles forming a single nanofluid or particle suspension, with localized anode and cathode sites for energy harvesting from particles **600** includes the following components: housing **602**, mixed anodic-cathodic nanofluid or particle suspension **604**, anode **606**, cathode **608**, load **610**, optional storage tank **612**, pump **614**, particle **618**, particle or ion **620**, particle **622**, and particle or ion **624**.

[0067] Electrical power is produced by anode **606** and cathode **608** being connected across load **610** by suitable electrical connectors. The housing **602** contains mixed anodic-cathodic nanofluid or particle suspension **604**. An anode **606** is shown as a functionalized species-specific anode **606** and the cathode **608** is shown as a functionalized species-specific cathode **608**. Nanoparticles or particles in mixed anodic-cathodic nanofluid or particle suspension **604** produce particle **618** and particle or ion **620** that interact with anode **606**. Nanoparticles or particles in mixed anodic-cathodic nanofluid or particle suspension **604** produce particle **622** and particle or ion **624** that interact with cathode **608**.

[0068] The mixed anodic-cathodic nanofluid or particle suspension **604** can be circulated to optional storage tank **612** through suitable fluid lines by pump **614**. The mixed anodic-cathodic nanofluid or particle suspension **604** is a nanofluid or particle suspension. The nanofluid is defined as: nanofluid=nanoparticles+dielectric or ionic fluid. A wide range of nanoparticles can be used. The particle suspension is defined as: particle suspension=particles+dielectric or ionic fluid. A wide range of particles can be used. Examples of nanoparticles and particles that can be used in the nanofluid or particle suspension are included in Table 1 above.

[0069] Nanofluid or Particle Suspension

[0070] Referring now to FIG. 7, a partial view of the reaction chambers of FIG. 1 is shown. The partial view of the reaction chambers is designated generally by the reference numeral **700**. The area **700** designated in FIG. 1 is shown to illustrate the nanofluid or particle suspension and the interaction of the nanofluid or particle suspension with contact separator and electrolyte layer **704**. The partial view of the reaction chambers includes the following components: nanofluid or particle suspension anolyte **702**, contact separator and electrolyte layer **704**, nanofluid or particle suspension catholyte **706**, porous metal contact (electro catalytic anode) **708**, porous metal contact (electro catalytic cathode) **710**,

particles in nanofluid or particle suspension swept along by fluid flow **712**, fluid flow arrow (nanofluid or particle suspension anolyte) **714**, and fluid flow arrow (nanofluid or particle suspension catholyte) **716**.

[0071] The nanofluid or particle suspension and the interaction of the nanofluid or particle suspension interacts with the porous metal contact (electro catalytic anode) **708**, porous metal contact (electro catalytic cathode) **710**, and separator and electrolyte layer **704**. The separator and electrolyte layer **704** is constructed of solid state electrolytes for an electrode separator-electrolyte layer. Examples of the solid state electrolytes for an electrode separator-electrolyte layer are shown in Table 2 above.

[0072] The particles **712** in the nanofluid or particle suspension are swept along by fluid flow as indicated by the fluid flow arrow (nanofluid or particle suspension anolyte) **714** and fluid flow arrow (nanofluid or particle suspension catholyte) **716**. The particles **712** in nanofluid or particle suspension anolyte **702** are shown contacting the porous metal contact (electro catalytic anode) **708** by impingement. The particles **712** in nanofluid or particle suspension catholyte **706** are shown contacting the porous metal contact (electro catalytic cathode) **710** by impingement. Examples of the particles **712** in the nanofluid or particle suspension are included in Table 1 above.

[0073] Some of the advantages of the nanofluid or particle suspension nanofluid or particle suspension anolyte **702** and the nanofluid or particle suspension catholyte **706** include: enhanced thermal management; prevention of thermal runaway in high capacity systems; overcoming solubility limit of encountered in liquid redox batteries by enlarging the storage volumes for anodic/cathodic nanofluids or particle suspensions; ability to provide unlimited capacity for a wide variety of chemistries; fast mechanical recharging; and extremely high charge and discharge rates for vehicular applications (extreme rate capability), enabled by the short diffusion length, coupled with flow-control of turbulence and mixing.

[0074] While the invention may be susceptible to various modifications and alternative forms, specific embodiments have been shown by way of example in the drawings and have been described in detail herein. However, it should be understood that the invention is not intended to be limited to the particular forms disclosed. Rather, the invention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the following appended claims.

The invention claimed is:

1. A battery apparatus that provides electrical energy across a load, comprising:

a battery housing having a first side, a second side opposite said first side, and an enclosure between said first side and said second side,

a solid electro-catalytic anode in said enclosure,

a nanofluid or particle suspension anolyte in said enclosure between said first side and said solid electro-catalytic anode providing a first section of the battery with said nanofluid or particle suspension anolyte in said first section

wherein said nanofluid or particle suspension anolyte includes nanoparticles that are lithium or lithium alloys,

a nanofluid or particle suspension anolyte storage unit,

a nanofluid or particle suspension anolyte circulation system for circulating said nanofluid or particle suspension

anolyte from said nanofluid or particle suspension anolyte storage unit to said first section,
 a solid electro-catalytic cathode in said enclosure,
 a nanofluid or particle suspension catholyte in said enclosure between said second side and said solid electro-catalytic cathode providing a second section of the battery with said nanofluid or particle suspension catholyte in said second section providing a nanofluid or particle suspension catholyte storage unit,
 a solid state electrolyte separator between said solid electro-catalytic anode and said solid electro-catalytic cathode,
 electrical connectors connecting said solid electro-catalytic anode and said solid electro-catalytic cathode across the load, and
 a nanofluid or particle suspension catholyte circulation system for circulating said nanofluid or particle suspension catholyte from said nanofluid or particle suspension catholyte storage unit to said second section, and
 an agitator in said enclosure.

2. The electro-chemical energy conversion and storage apparatus of claim 1 wherein said nanofluid or particle suspension includes nanoparticles and a dielectric or ionic fluid.

3. The energy storage battery apparatus of claim 1 wherein said nanofluid or particle suspension anolyte is a particle suspension that includes anodic hydride nanoparticles and a dielectric or ionic fluid.

4. The electro-chemical energy conversion and storage apparatus of claim 2 wherein said nanoparticles are hydrides as a source of hydrogen ions.

5. The electro-chemical energy conversion and storage apparatus of claim 2 wherein said nanoparticles are lithium or lithium alloys.

6. The electro-chemical energy conversion and storage apparatus of claim 2 wherein said nanoparticles are intercalated graphite or carbon aerogel as a Li source.

7. The electro-chemical energy conversion and storage apparatus of claim 2 wherein said nanoparticles are intercalated transition metal oxide as a Li source.

8. The electro-chemical energy conversion and storage apparatus of claim 1 wherein said circulation system includes a pump.

9. The energy storage battery apparatus of claim 1 wherein said nanofluid or particle suspension catholyte is a nanofluid that includes nanoparticles and a dielectric or ionic fluid.

10. The electro-chemical energy conversion and storage apparatus of claim 1 wherein said circulation system includes a nanoparticle supply and a fluid supply.

11. The electro-chemical energy conversion and storage apparatus of claim 1 wherein said circulation system includes a vessel having a rounded bottom a nanoparticle supply, a fluid supply, and an agitator.

12. The energy storage battery apparatus of claim 1 wherein said nanofluid or particle suspension anolyte is a nanofluid that includes nanoparticles and a dielectric or ionic fluid.

13. The energy storage battery apparatus of claim 1 wherein said nanofluid or particle suspension anolyte is a nanofluid that includes lithium nanoparticles and a dielectric or ionic fluid.

14. The battery apparatus of claim 1 wherein said solid state electrolyte separator is positioned between said solid electro-catalytic anode and said solid electro-catalytic cathode and is in direct contact with said electro-catalytic anode and said solid electro-catalytic cathode and wherein said a solid state electrolyte separator includes plasticized solid polymer electrolytes (SPEs).

15. A battery apparatus that provides electrical energy across a load, comprising:

a battery housing having a first side, a second side opposite said first side, and an enclosure between said first side and said second side having an anode compartment immediately adjacent said first side and a cathode compartment immediately adjacent said second side,
 a solid electro-catalytic anode in said anode compartment of said enclosure,

a particle suspension anolyte in said anode compartment between said first side and said solid electro-catalytic anode

wherein said particle suspension anolyte includes nanoparticles that are lithium or lithium alloys,

a particle suspension anolyte storage unit,

an anolyte circulation system for circulating said particle suspension anolyte from said particle suspension anolyte storage unit to said anode compartment,

a solid electro-catalytic cathode in said cathode compartment,

a particle suspension in said cathode compartment between said second side and said solid electro-catalytic cathode, a particle suspension catholyte storage unit,

a solid state electrolyte separator between and in direct contact with said solid electro-catalytic anode and said solid electro-catalytic cathode thereby separating said anode compartment from said cathode compartment, electrical connectors connecting said solid electro-catalytic anode and said solid electro-catalytic cathode across the load,

a catholyte circulation system for circulating said catholyte from said particle suspension catholyte storage unit to said cathode compartment, and

an agitator in said enclosure.

16. The energy storage battery apparatus of claim 15 wherein said particle suspension anolyte is a particle suspension that includes anodic hydride nanoparticles and a dielectric or ionic fluid.

17. The electro-chemical energy conversion and storage apparatus of claim 16 wherein said anodic hydride nanoparticles are hydrides as a source of hydrogen ions.

18. The energy storage battery apparatus of claim 15 wherein said particle suspension anolyte includes lithium or lithium alloys nanoparticles and a dielectric or ionic fluid.

* * * * *

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Abstract:

The disclosure relates to particle heaters for heating solid particles to store electrical energy as thermal energy. Thermal energy storage directly converts off-peak electricity into heat for thermal energy storage, which may be converted back to electricity, for example during peak-hour power generation. The particle heater is an integral part of an electro-thermal energy storage system, as it enables the conversion of electrical energy into thermal energy. As described herein, particle heater designs are described that provide efficient heating of solid particles in an efficient and compact configuration to achieve high energy density and low cost.

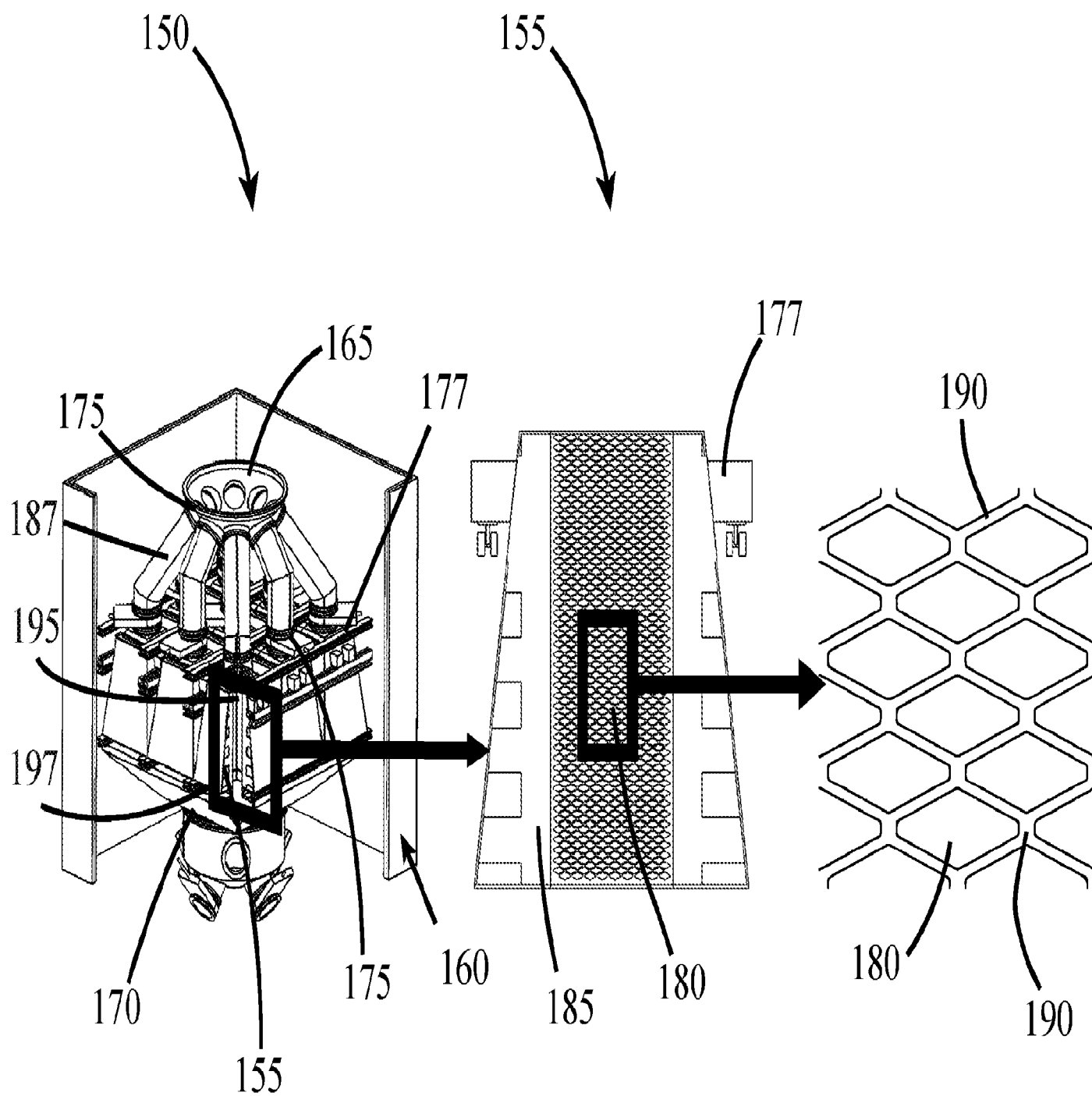


Figure 1B

ELECTRIC CHARGING PARTICLE HEATER FOR THERMAL ENERGY STORAGE

CROSS-REFERENCE TO RELATED APPLICATIONS

5 This application claims priority from U.S. Provisional Patent Application No. 63/051,534 filed on July 14, 2020, the contents of which are incorporated herein by reference in their entirety.

CONTRACTUAL ORIGIN

This invention was made with government support under Contract No. DE-AC36-08GO28308 awarded by the Department of Energy. The government has certain rights in the invention.

BACKGROUND

10 Renewable energy resources have been limited by the ability to store energy produced during off-peak times for use during peak times. Energy storage is important for variable-regeneration renewable energy sources, such as wind and solar. However, current battery technologies are too expensive for grid-scale, long duration energy storage. Molten salt storage is expensive and limited by salt stability and corrosion issues. Pumped energy storage in the form of hydroelectricity is limited by the
15 geological conditions of the system as it requires two reservoirs at different vertical levels. Thus, there remains a need for improved energy storage systems capable of storing excess electricity produced by alternative energy sources such as wind and solar, to be recovered later during peak electricity demand.

SUMMARY

20 An aspect of the present disclosure is a heater for heating a plurality of solid particles, the heater including at least two three-dimensional (3D) shapes, each 3D shape including at least two surfaces, in which each surface of each 3D shape includes at least two lateral edges positioned substantially parallel to a first axis (z), each lateral edge has a length between a proximal end and a distal end, each surface includes a proximal edge positioned at the proximal end of the length
25 and within a first plane defined by a second axis (x) and a third axis (y), the proximal edges of each surface of each 3D shape form a cross-sectional shape in the plane, at least one surface of each 3D shape is positioned to face at least one surface of another 3D shape defining a channel, the channel is oriented to enable the gravitational flow of the plurality of solid particles through the channel, at least one surface defining the channel is configured to transfer heat to at least a

portion of the plurality of solid particles, x and y are each perpendicular to z, and x and y are perpendicular to each other.

In some embodiments, the at least one surface defining the channel is configured to operate at a temperature between about 500 °C to about 1500 °C. In some embodiments, the cross-sectional shape is a polygon. In some embodiments, the polygon has an interior angle defined as the angle between x and a proximal edge, and the interior angle is in the range of about 5° to about 60°. In some embodiments, the interior angle is approximately 10°. In some embodiments, the polygon is a triangle, a quadrilateral, a pentagon, a hexagon, a heptagon, an octagon, a nonagon, or a decagon. In some embodiments, the at least one surface defining the channel configured to transfer heat comprises a resistive heating element. In some embodiments, the resistive heating element is positioned within an indentation in the at least one surface defining the channel. In some embodiments, the resistive heating element comprises an electric-resisting wire or bar. In some embodiments, the channel has a height substantially parallel with y. In some embodiments, the height is in the range of about 0.05 m to about 1.5 m. In some embodiments, the height is approximately 0.15 m. In some embodiments, the channel has a width substantially parallel with x. In some embodiments, the width is in the range of about 0.05 m to about 1.5 m. In some embodiments, the width is approximately 0.15 m. In some embodiments, a block positioned between the at least two 3D shapes and filling at least a portion of the channel and the block is configured to maintain the width of the channel. In some embodiments, the block comprises a substantially insulative material. In some embodiments, the block is further configured to direct the plurality of solid particles towards the at least one surface defining the channel configured to transfer heat

An aspect of the present disclosure is a particle heater configured to heat a plurality of solid particles, the particle heater including a heater module having an inlet and an outlet and substantially filled with a plurality of heating elements which define a plurality of channels, in which the plurality of heating elements are configured to direct the plurality of solid particles through the plurality of channels, the plurality of heating elements are configured to receive electrical energy to generate heat resulting in heating of the plurality of solid particles from a temperature at the inlet between about 250 °C and about 500 °C to a temperature at the outlet between about 850 °C and about 1,200 °C.

An aspect of the present disclosure is a method of heating a plurality of solid particles, the method including receiving the plurality of solid particles to an inlet of a heater module substantially filled with a plurality of heating elements which define a plurality of channels, directing the plurality of solid particles through the plurality of channels, heating the plurality of solid particles from a temperature at the inlet between about 250 °C and about 500 °C to a temperature at an outlet of the heater module between about 850 °C and about 1,200 °C using the plurality of heating elements, and removing the plurality of solid particles from the heater module via the outlet, in which the plurality of heating elements are configured to receive an electrical energy and convert the electrical energy to a thermal energy for the heating.

BRIEF DESCRIPTION OF THE DRAWINGS

Some embodiments of the present disclosure are illustrated in the referenced figures of the drawings. It is intended that the embodiments and figures disclosed herein are to be considered illustrative rather than limiting.

Figure 1A illustrates a thermal energy storage system, including particle heater, according to some embodiments of the present disclosure.

Figure 1B illustrates a particle heater, according to some embodiments of the present disclosure.

Figure 1C illustrates heating elements which may be used in a particle heater, according to some embodiments of the present disclosure.

Figure 1D illustrates an exemplary heating element which may be used in a particle heater, according to some embodiments of the present disclosure.

Figure 2 illustrates a flowchart describing a method for converting electrical energy to thermal energy, and the thermal energy back to electrical energy, according to some embodiments of the present disclosure.

Figure 3 illustrates a process flow diagram of the flow of solid particles through the electric charging process, according to some embodiments of the present disclosure.

Figure 4 illustrates photographs of exemplary heating elements, according to some embodiments of the present disclosure.

Figure 5 illustrates a cross-sectional shape of a heating element showing the location of an interior

inclination angle, according to some embodiments of the present disclosure.

Figure 6 illustrates average solid particle temperatures (x-axis) for different inclination angles of heating elements at various vertical positions (y-axis, particles flow from the position to negative y-direction), according to some embodiments of the present disclosure.

- 5 Figure 7 illustrates modeling results of contours of the gas fraction (1.00 meaning no particles, 0.42 meaning packed bed) throughout the modeled domain for different inclination angles, according to some embodiments of the present disclosure. Grey contour shows the full solid particle domain for a 10° geometry.

- 10 Figure 8 illustrates discrete element method (DEM) simulation results of solid particle velocities for a no friction case and a 0.15 friction case, according to some embodiments of the present disclosure.

Figure 9 illustrates DEM results of gas fractions in a 30° heater with two different friction coefficients, according to some embodiments of the present disclosure.

- 15 Figure 10 compares the results obtained from an analytical model for a short and medium height simulations of a heater module, according to some embodiments of the present disclosure. Also shown are the DEM solid particle temperature curves to verify the analytical model follows.

- 20 Figure 11 demonstrates results from an analytical model of the analytical temperature profile of a taller particle heater height based on the DEM simulation results obtained for a shorter particle heater, according to some embodiments of the present disclosure. The point marks the predicted height of the heater required to reach a target temperature of approximately 1,200 °C.

Figure 12 illustrates features of exemplary heating elements designed for a heater module, according to some embodiments of the present disclosure.

- 25 Figure 13 illustrates solid particle inlet (i.e., distributor) and outtake (i.e., collector) for the modular heater integration and exemplary particle flow control and distribution components, according to some embodiments of the present disclosure.

Figure 14 illustrates a cross-section of a single heater module, according to some embodiments of the present disclosure.

Figure 15 illustrates the full geometry with material types for a finite element analysis (FEA)

thermal model of a heater module's insulation, according to some embodiments of the present disclosure. The insulation material is displayed as transparent to show the presence of the supporting rods composed of the refractory material.

Figure 16 provides a model description with applied boundary conditions: (1) variable convection (1.0-10.0 W/m²-K) on exterior wall of the steel shell with a fixed ambient temperature and (2) a wall temperature profile as a function of position, both linear and exponential profiles were used, according to some embodiments of the present disclosure.

REFERENCE NUMERALS

	100.....energy storage system
10	101.....silo
	102.....solid particles and/or solid particle stream
	103.....turbine
	104.....generator or motor
	105.....substation
15	106.....grid line
	107.....particle conveyor
	109.....electrical supply line
	110.....working fluid and/or working fluid stream
	111.....fluidized bed heat exchanger
20	112.....shaft
	150.....particle heater
	155.....heater module
	160.....housing
	165.....first vessel (particle distributor)
25	170.....second vessel (particle collector)
	175.....valve
	177.....I-beam
	180.....heating element
	181.....surface
30	183.....cross-sectional shape
	184.....length (L)

	185.....	insulation
	186.....	lateral edge
	187.....	duct
	188.....	indentation
5	189.....	support
	190.....	channel
	191.....	proximal edge
	193.....	distal edge
	194.....	wire
10	195.....	inlet
	197.....	outlet

DETAILED DESCRIPTION

The present disclosure may address one or more of the problems and deficiencies of the prior art discussed above. However, it is contemplated that some embodiments as disclosed herein may prove useful in addressing other problems and deficiencies in a number of technical areas. Therefore, the embodiments described herein should not necessarily be construed as limited to addressing any of the particular problems or deficiencies discussed herein.

References in the specification to “one embodiment”, “an embodiment”, “an example embodiment”, “some embodiments”, etc., indicate that the embodiment described may include a particular feature, structure, or characteristic, but every embodiment may not necessarily include the particular feature, structure, or characteristic. Moreover, such phrases are not necessarily referring to the same embodiment. Further, when a particular feature, structure, or characteristic is described in connection with an embodiment, it is submitted that it is within the knowledge of one skilled in the art to affect such feature, structure, or characteristic in connection with other embodiments whether or not explicitly described.

As used herein the term “substantially” is used to indicate that exact values are not necessarily attainable. By way of example, one of ordinary skill in the art will understand that in some chemical reactions 100% conversion of a reactant is possible, yet unlikely. Most of a reactant may be converted to a product and conversion of the reactant may asymptotically approach 100% conversion. So, although from a practical perspective 100% of the reactant is converted, from a

technical perspective, a small and sometimes difficult to define amount remains. For this example of a chemical reactant, that amount may be relatively easily defined by the detection limits of the instrument used to test for it. However, in many cases, this amount may not be easily defined, hence the use of the term “substantially”. In some embodiments of the present invention, the term “substantially” is defined as approaching a specific numeric value or target to within 20%, 15%, 10%, 5%, or within 1% of the value or target. In further embodiments of the present invention, the term “substantially” is defined as approaching a specific numeric value or target to within 1%, 0.9%, 0.8%, 0.7%, 0.6%, 0.5%, 0.4%, 0.3%, 0.2%, or 0.1% of the value or target.

As used herein, the term “about” is used to indicate that exact values are not necessarily attainable.

Therefore, the term “about” is used to indicate this uncertainty limit. In some embodiments of the present invention, the term “about” is used to indicate an uncertainty limit of less than or equal to $\pm 20\%$, $\pm 15\%$, $\pm 10\%$, $\pm 5\%$, or $\pm 1\%$ of a specific numeric value or target. In some embodiments of the present invention, the term “about” is used to indicate an uncertainty limit of less than or equal to $\pm 1\%$, $\pm 0.9\%$, $\pm 0.8\%$, $\pm 0.7\%$, $\pm 0.6\%$, $\pm 0.5\%$, $\pm 0.4\%$, $\pm 0.3\%$, $\pm 0.2\%$, or $\pm 0.1\%$ of a specific numeric value or target.

Among other things, the present disclosure relates to heaters for heating solid particles to store electrical energy as thermal energy. Electro-thermal energy storage directly converts off-peak electricity into heat for thermal energy storage, which may be converted back to electricity, for example during peak-hour power generation. Thus, electro-thermal energy storage will, among other things, enable better incorporation of intermittent renewable energy sources such as solar and wind into existing electrical grids, which will in turn result in improved grid resilience. The particle heater is important part of an electro-thermal energy storage system, as it enables the conversion of electrical energy into thermal energy. Thus, among other things, the present disclosure describes electric particle heaters for this important energy conversion step. As described herein, particle heater designs are described that provide efficient heating of solid particles in an efficient and compact configuration to achieve high energy density and low cost.

Figure 1A illustrates an energy storage system 100, including a particle heater 150, according to some embodiments of the present disclosure. In this exemplary energy storage system 100, a silo 101 (i.e., a storage vessel; four shown 101A-D) is provided, which may be utilized for the storage of solid particles 102. A particle heater 150, as described in detail herein, may be positioned near

and/or inside the silo 101, such that the particle heater 150 is configured to heat the solid particles 102 from a first relatively low temperature of between about 250°C and about 500°C to a second relatively high temperature between about 850 °C and about 1,200 °C prior to the solid particles 102 entering a silo 101 during a “charging mode”, where the solid particles 102 are heated using electricity. Thus, a particle heater 150 may be an electric heater (e.g., using resistive heating elements), with the electric power needed to drive the electric heater provided from the grid as shown by electrical supply line 109 shown in Figure 1A. The heated solid particles 102, and the thermal energy stored within the solid particles 102, may then be stored within a silo 101 until such a time when the local or regional electrical needs (e.g., time periods of peak electrical energy usage) require that the thermal energy stored in the heated solid particles 102 be converted back to electricity.

In some embodiments of the present disclosure, the thermal energy stored in the solid particles 102 may be converted to electricity by passing the heated solid particles 102 through a fluidized bed heat exchanger 111 that transfers heat from the particles 102 to a heat transfer fluid (i.e., a working fluid and/or working fluid stream 110). For example, the hot solid particles 102 may be transported from the silo 102 to a fluidized bed heat exchanger 111 in which the hot solid particles 102 come into direct contact with the working fluid 110. As shown in Figure 1A, in some embodiments of the present disclosure, a fluidized bed heat exchanger 111 may be an integral component of a silo 102, such that the hot solid particles 102 may be transported by gravity from within the silo 102 to the fluidized bed heat exchanger 111. In some embodiments of the present disclosure, for example when the fluidized bed heat exchanger 111 is not an integral part of the silo 102, the hot solid particles 102 may be transported to a fluidized bed heat exchanger 111 gravitationally, pneumatically, and/or mechanically (e.g., by the use of a conveyor similar to particle conveyor 107). As shown in Figure 1A, a fluidized bed heat exchanger 111 may be configured to transfer thermal energy (i.e., heat) from the solid particles 101 to a working fluid 110 (i.e., an inert gas or heat transfer fluid), thereby heating the working fluid 110 to a temperature between about 700 °C and about 1,200 °C and cooling the solid particles 102 to a temperature between about 250 °C and about 500 °C. The heated working fluid 110 may be subsequently directed to a turbine 103, which in turn may drive a shaft 112 connected to a generator or motor 104, such that at least a portion of the thermal energy recovered from the solid particles is converted to electrical energy 109, which may then be transferred to a substation 105 and finally to a grid line 106 for transport to the power

grid. The now expanded and cooled working fluid 110 may then be directed to a compressor (not shown) to provide the driving force needed to circulate the working fluid 110 back through the fluidized bed heat exchanger 111.

Figure 2 illustrates a flowchart describing a method for converting electrical energy to thermal energy, and the thermal energy back to electrical energy, according to some embodiments of the present disclosure. As shown in Figure 2, using electrical energy from the electricity grid (i.e., the substation 105 and supplied by the grid line 106) the particle heater 150 may “charge” the energy storage system 100 by heating the solid particles 102 (“particle charging flow”). Then the solid particles 102 may be used for thermal energy storage (TES) (“particle discharging flow”) by storing the heated solid particles 102 in a silo 101. Finally, the heated solid particles 102 may be used to transfer thermal energy to a working fluid 110, such as a gas, which can be used to generate electricity (“discharging power”).

Referring again to Figure 1A, a particle heater 150 is an important component of the energy storage system 100 whose design may significantly affect the overall performance metrics of the energy storage system 100. Thus, among other things, the present disclosure describes particle heaters 150 that are very effective at heating solid particles 102 using electricity as the energy input to the particle heater 150. For example, to achieve high heat transfer rates, in order to reduce the heater size and raw materials needed (and thus reduce capital costs), an array of heating elements may be strategically arranged to maximize the heat transfer between the electric heating elements and the solid particles in contact with the electric heating element, and by directing the solid particles to the electric heating elements in a granular flow pattern. In addition, in some embodiments of the present disclosure, a large-scale particle heater 150 may be provided in a modular design to optimize operation and flow patterns through the individual heating elements while enabling redundancy in the overall particle heater 150. Methods of fabricating electric heating elements are also described herein.

Figure 1B illustrates a particle heater 150, according to some embodiments of the present disclosure. In this example, the particle heater 150 contains nine heater modules 155 (only one called out by a reference number), positioned within a larger housing 160. The housing 160 may be insulated or may serve to insulate or protect the heater modules 155 from external elements. Each heater module 155 may be connected to at least one I-beam 177 (or other form of support)

which not only provides structural support but may also enable quick removal of individual heater modules 155 from the particle heater 150 when necessary. Solid particles (not shown) may be directed to the particle heater 150 from a particle distributor 165, which directs the relatively cold solid particles to each of the heater modules 155 that are in use (or “on-line”). A gate-valve 175
5 may be utilized to turn on and turn off particle flow to a specific heater module 155, thus, enabling stepwise increases and decreases to the particle heater’s 150 particle flow rate and heating rate. The heated solid particles may then exit the various heater modules 155 to fall into a particle collector 170, which may also be fitted with gate valves 175.

Referring to the center panel of Figure 1B, each heater module 155 may be constructed of a
10 plurality of electrically powered heating elements 180 positioned with insulation 185 (e.g., a refractory or nonconductive material) to minimize heat losses from the heater module 155 and for personnel safety. The insulation 185 may be connected directly to I-beams 177. As shown in the right panel of Figure 1B, the heating elements 180 may create a network of channels 190 through which the solid particles 102 may flow or fall by gravity (or may be pumped or forced through),
15 contacting the hot surfaces of the heating elements 180, resulting in the transfer of heat to the solid particles, thus completing the conversion of electrical energy to thermal energy.

Figure 1C illustrates heating elements 180, according to some embodiments of the present disclosure. The heating elements 180 may be three-dimensional (3D) shapes. Each heating element 180 may have at least two surfaces 181 with at least two lateral edges 186 positioned substantially
20 parallel to a first axis (z). Each heating element 180 and lateral edge 186 has a length 184 between a proximal end and a distal end. Each surface has a proximal edge 191 positioned at the proximal end of the length 184 and within a first plane defined by a second axis (x) and a third axis (y). The proximal edges 191 form a cross-sectional shape 183 in the plane. At least one surface 181 of each heating element 180 is positioned to face at least one surface 181 of another heating element 180
25 to define a channel 190. The channel 190 is oriented to enable the gravitational flow of the plurality of solid particles through the channel 190. At least one surface 181 defining the channel 190 is configured to transfer heat to at least a portion of the plurality of solid particles (not shown in Figure 1C). For orientation purposes, x and y are each perpendicular to z, and x and y are perpendicular to each other.

The surfaces 181 of the heating elements 180 may be substantially planar. The surfaces 181 may be convex, concave, or substantially flat (that is, not having a significant curvature). The surfaces may be capable of transferring heat (i.e., conductive) or may be capable of converting electrical energy to thermal energy (i.e., heat “generating”). The length 184 of the heating elements 180 may be substantially similar to the measurement of a heater module 155 in the z direction. That is, the heating elements 180 may substantially fill a heater module 155 in the z direction.

The channel 190 may be defined by the arrangement of the heating elements 180 within a heater module 155 and may be “negative space” (i.e., empty space). The channel 190 may be large enough that at least one solid particle 102 can flow through the channel 190 without becoming stuck. The channel 190 may curve around heating elements 180 such that the channel 190 extends in multiple directions.

In some embodiments, the cross-sectional shape 183 may have any number of sides. In some embodiments, the cross-sectional shape 183 may be a polygon having substantially straight sides. The polygon may be a triangle, a quadrilateral, a pentagon, a hexagon, a heptagon, an octagon, a nonagon, decagon, or n-gon (where n is an integer). The polygon may be a regular polygon being substantially equilateral (i.e., having sides of approximately equal length) and/or equiangular (i.e., having interior angles of approximately equivalent angles). The polygon may be irregular, having sides of varying length and interior angles of varying degrees. In other embodiments, the cross-sectional shape 183 may be a Reuleaux polygon having at least one side which is not substantially straight. The Reuleaux polygon may be a regular Reuleaux polygon with curves of constant width formed by a finite number of circular arcs of equal length or may be an irregular Reuleaux polygon with curves of varying width based on a finite number of circular and/or non-circular arcs of varying lengths. In some embodiments, the cross-sectional shape 183 may be a multi-sided shape with some curved sides and some substantially straight sides.

Figure 1D illustrates an exemplary heating element 180, according to some embodiments of the present disclosure. The exemplary heating element 180 has a cross-sectional shape 183 of a square with curved corners. An indentation 188 wraps around the heating element 180 multiple times to allow a wire, bar, or other resistive heating element (not shown) to be placed within the indentation 188. A support 189 extends through both the proximal end and distal end of the heating element 180 and may be used to align the heating element 180 in the heater module 155. The exemplary

heating element 180 may be made primarily of a conductive material to allow for heat to be transferred from the resistive heating element to the solid particles 102 (not shown).

Electricity storage by thermal energy storage (TES) may use energy storage media (i.e., solid particles) capable of remaining stable over the desired operating temperature range, and ideally capable of demonstrating superior fluidization and heat-transfer properties. Table 1 shows a summary of four potential solid particle materials, and relevant properties. These potential solid particles may be screened based on their stability at temperatures greater than 1,100 °C, relative energy densities, cost of acquisition and particle preparation, and regional abundance. A plurality of solid particles or solid particle flow 102 as described herein may include any combination of energy storage media or other similar media options.

Table 1. Relevant properties for potential storage media

ID	Media	Media Properties		
		Density (kg/m ³)	C _p (J/kg-K)	Melting T (°C)
1	Coal (fly) ash	~2,000	1,098	1,183–1,640
2	Silica sand (β-quartz)	2,650	1,155	1,710
3	Calcined flint clay	2,500	1,050	1,500
4	Brown fused alumina	3,950	1,321	2,000

Figure 3 illustrates a particle flow diagram for the “charging” step (i.e., electrical heating of the solid particles using the energy storage system 100) according to some embodiments of the present disclosure. In this example, relatively cool solid particles may be removed from a storage silo 101 and transported through a particle lifting device (a skip hoist in this example as a particle conveyor 107) to the top of the particle heater 150. The solid particles 102 may then be distributed (through a particle distributor 165) to various inlets of the heater modules 155 of the particle heater 150 to be contacted (e.g., by flowing gravitationally) with the various heating elements 180. The heated solid particles 102 may then flow through a control valve 175 to a designated storage silo 101. For the energy “discharging” step, (i.e., conversion of the solid particles’ thermal energy to electrical energy) the heated solid particles 102 may be directed to a heat exchanger, (e.g., a pressurized fluidized bed heat exchanger 111) to be contacted with and heat compressed air delivered from a turbine 103 that then utilized the heated air to drive the turbine 103 to generate electrical power. In some embodiments of the present disclosure, a particle heater 150 may have a modular design that can be adapted to suit various commercial scales. In addition, the particle heaters 150

described herein were designed to be constructed from commercially available, high temperature materials from among other industries, including the refractory industry.

Heat transfer from a surface to a solid particle depends strongly on both particle-surface and particle-particle interactions including particle-surface contact, particle mixing, particle flow regime, and particle thermal properties. Improving the particle-surface heat transfer in a particle heat exchanger 150 is beneficial because the particle-surface heat transfer (i.e., heat transfer between solid particles 102 and a surface 181 of a heating element 180) controls the overall particle heater 150 size and cost. The particle-surface heat transfer largely depends on the design of the particle flow regime.

Electric charging particle heater design innovations described herein include:

- Modular particle heaters for rapid response to input charging power variations
- Aiming at a high-efficiency, low-cost design
- Low-cost materials for low-cost charging heater

The lower cost results in the electric particle heaters described herein having charging capacities that can be larger than the power generation capacity of the system. This means the energy storage system can store large amounts of electricity in a short period time for a very low price.

In some embodiments of the present disclosure, a particle heater may be designed in modular sections (e.g., a three-by-three modular assembly as shown in Figure 5). Such a modular heater design has several practical as well as novel features compared to a single, 300-MW heater design.

An individual heater module may be swapped in and out for maintenance while other modules remain functional.

In some embodiments of the present disclosure, the individual heater modules 155 of a particle heater 150 may be operated at fixed design conditions (e.g., fixed electrical power input, mass flow rate, inlet temperature and/or outlet temperature) for a fixed electric charging load. By turning on/off individual heater modules 155, a complete particle heater 150 constructed of multiple heater modules 155 may follow the available electrical load in a stepwise ramping manner (e.g., changing electrical charging loads may be matched by turning one or more individual heater modules on or off, as needed). For instance, in the case of the design shown in Figure 1B, a particle heater 150 may be designed to accommodate nine discrete electrical charging loads by providing nine discreet

heater modules to match the discrete electrical loads. However, nine heater modules 155 are chosen for illustrative purposes only and different applications may have more or fewer heater modules 155, depending on each application's specific needs. Each individual heater module 155 may operate at uniform design conditions and may be optimized for a single solid particle flow rate and electric charging load to achieve the designed outlet temperature for the solid particles. Among other things, these load following steps simplify the charging control mechanism and particle flow control, while ensuring that the heaters will always run under optimal conditions.

In some embodiments of the present disclosure, heater modules 155 may be supported on I-Beam rails, which may be subsequently attached to an external support structure. The individual heater modules may then be rolled out of the assembly enclosure for repair or maintenance, without removing the entire particle heater, with all of its individual modules, from service. I-Beam rails may be attached to an external support structure. In some embodiments of the present disclosure, refractory, the first insulation layer of the individual heater modules, may be cast with support structures that transfer the structural load to the metal support rods on the outside of the metal casing (i.e., refractory 185 in center panel of Figure 1B).

In some embodiments of the present disclosure, the temperature of a solid particle may increase continuously when flowing/falling through and contacting the heating elements 180 contained in a particle heater 150 to reach a target temperature (e.g., 1,200 °C). Solid particle recirculation for additional heating may not be needed with sufficient heating provided by the heater modules 155 of a particle heater 150 after one pass through the heater modules 155. Among other things, this eliminates any need for mechanical complexities for transporting the solid particles at high temperatures. Thus, in some embodiments of the present disclosure, heated solid particles 102 may fall into a hopper and the flow may be controlled by gate valves 175 to subsequently guide the solid particles 102 into a designated storage silo 101.

An enclosure (i.e., housing 160) may be provided to house the electrical connections needed for the heating elements 180. To keep the particle heater 150 temperature within the allowable temperature ranges of the structural, electric cables, etc., each heater module 155 may be insulated to maintain a temperature inside the housing 160 but outside of the particle heater 150 below at an acceptable set-point (e.g., about 350 °C). The housing 160 may provide insulation to separate the external structures from the high temperatures of the heating elements 180 within the heater

modules 155. Also, housing 160 prevents heat loss from an active heater module 155 (i.e., electrically heating solid particles 102) to an inactive heater module 155 (i.e., turned “off” and not supplying heat to solid particles 102), for example, during partial load charging scenarios. The housing 160 of the particle heater 150 assembly may be further insulated from the ambient conditions. A preliminary thermal analysis of the housing 160 design for a single heater module 155 has been conducted and is presented herein.

As described herein, a particle heater (constructed of two or more heater modules) may include three sections through which the solid particles may flow: 1) a distributor, 2) heater module, and 3) collector. In some embodiments of the present disclosure, a distributor may use a gate valve to control which heater module(s) receives the relatively cool solid particles at, for example, about 300 °C. Each heater module may contain hundreds of individual heating elements. As described above, each the individual heating elements of a heater module of a particle heater heat the solid particles to a target temperature (e.g., about 1,200 °C). A single collector may then collect the heated solid particles from each of the heater modules to subsequently direct them to one or more insulated storage silos using gate valves.

The individual heating elements within a heater module may be tasked with supplying the thermal power necessary to heat the solid particles. A full, commercial-scale heater may need to be able to consume in excess of 300 MWe of electrical energy. Table 2 summarizes some key design parameters for a heater module, according to some embodiments of the present disclosure. These parameters were calculated using a heat-mass balance; the solid particle flow and heat transfer modeling using discrete element methods is introduced below. The values summarized in Table 2 serve as good starting design points, and are not necessarily fixed (e.g., the particle mass flux per inlet area could range from 40-60 kg/s-m²), and may change depending on specific applications, climates, etc.

Table 2. Exemplary design parameters for a commercial-scale heater module.

Parameter	Variable	Value	Units	Notes/Equations
Particle mass flux per inlet area	m''	40	kg/s-m ²	40-60 range possible
Module heater inlet area	A_i	1.0	m ²	Chosen
Total heater inlet area	A_{tot}	9.0	m ²	9 modules
Module heater inlet mass flow rate	m_i	40	kg/s	$m_i = m'' A_i$
Total heater inlet mass flow rate	m_{tot}	360	kg/s	$m_{tot} = m'' A_{tot}$
Temperature change	ΔT	900	K	$\Delta T = (1200-300) ^\circ\text{C}$
Module heater thermal power	P_i	41.56	MWt	$P_i = m_i C_p \Delta T$
Total heater thermal power	P_{tot}	374.06	MWt	$P_{tot} = m_{tot} C_p \Delta T$
Number of heating elements	N_{el}	774	-	From Solidworks
Module heating element thermal power	P_{el}	53.70	kWt	$P_{el} = P_{tot}/N_{el}$
Thermal power per element length	P'_{el}	53.70	kWt/m	$P'_{el} = P_{el}/(A_i^{0.5})$

Particle flow and heat transfer through heater modules and past heating elements were modeled as described below. Among other things, the particle flow patterns through arrays of heating elements determine the particle flow rates, residence times, heat transfer, and energy absorption. The heat transfer in a moving bed was analyzed by using a discrete element method (DEM) model developed in MFIX (Multiphase Flow Interface eXchange Model), a commercially available software tool.

Figure 4 illustrates photographs of exemplary heating elements 180, according to some embodiments of the present disclosure. The upper panel shows an exemplary heating element 180 of a refractory material wrapped in a wire for resistive heating. The heating element 180 has a cross-sectional shape 183 of a hexagon (or a square with curved corners) with four surfaces 181. The wire is in contact with each surface 181 such that each surface 181 can facilitate heat transfer to solid particles 102. The lower panel shows an exemplary arrangement of heating elements 180 arranged to form channels 190. The heating elements 180 are arranged such that while flowing through the channels 190 the solid particles 102 may be in contact with at least one surface 181 with a resistive heating element (i.e., a wire or a metal bar) for heating of the solid particles 102. In some instances, the solid particles 102 may be in between two surfaces 181 which both may be capable of transferring heat from the resistive heating element to the solid particles 102.

Figure 5 illustrates a cross-sectional shape 183 at an end of a heating element 180 showing an interior angle, which may also be referred to as an inclination angle. The inclination angle may be measured from the horizontal and may be at the intersection of two proximal edges 191 or two

distal edges 193. The inclination angle may impact the flow of solid particles 102 through the channel 190 (not shown). The higher the inclination angle, the steeper the channel, and the lower the inclination angle, the less steep the slope of the channel.

A particle diameter of silica sand of 450 microns (μm) was used as solid particles 102 in the simulation; the simulations did not consider the effects of polydispersity of solid particle size distributions. Two parameters were investigated to maximize the heat transfer from the heating elements 180 to the solid particles 102: surface angle and friction. Figure 6 shows the temperature rise (positive x-axis) as the solid particles descend through the heater module 155 (negative y-axis) as well as the effect of the inclination angle of the heating elements 180 on particle temperature rise. The inclination angles explored were 10° , 20° , and 30° measured from the horizontal. The gray sketch in Figure 7 shows the full particle domain with a 10° heater inclination angle. For the simulations, the cross-sectional shapes 183 were cut in half along the center vertical symmetry line to reduce the computational requirement. In the shaded contours shown in Figure 7, the solid particles 102 can be seen flowing along the surfaces 181 of the heating elements 180. This is a key takeaway from this simulation as it demonstrates hexagonal cross-sectional shapes 183 of heating elements 180 can effectively control the solid particle flow and heat transfer to the solid particles 102.

The solid particle mass flux through the particle heater 150 configuration may increase with increasing inclination angle; the inclination angles of 10° and 30° had a solid particle mass flux of 39 and 91 $\text{kg}/\text{m}^2\text{-s}$, respectively. Consequently, the residence time of the solid particles 102 in a domain with a larger inclination angle is shorter; thus, the solid particles 102 experience less of a temperature rise for the same number of heating elements 180. This effect is shown in Figure 6. Because the residence time is much longer for an inclination of 10° in the heating elements 180, the solid particles reached higher temperatures in a shorter distance than the 20° or 30° configurations. In each of these initial simulations, only several rows of heating elements 180 were modeled (each row has two heating elements 180 forming a single channel 190 with a height of about 0.3 m) whereas the actual particle heater 150 may have many more rows of heater elements 180 and/or heating elements 180 of a different size than what was modeled. For example, in some embodiments, the particle heater 150 may have about ten to fifty rows of two heating elements 180 and/or a height of about 2 m to about 4 m. In some embodiments, the heating elements 180 may be arranged in rows having more than two heating elements 180. An analytical method was

used that will be introduced below to use the results from this DEM simulation of a short section of heating elements 180 to predict the temperature rise for a full-size particle heater 150. For solid particles 102 with particle diameters of about 250 μm , the inclination angle may be about 70°.

Table 3 shows how the inlet solid particle mass flux, solid particle mass flow rate, solid particle temperature rise, and solid particle residence time vary with inclination angle. As was discovered, the lowest inclination angle (10°) had the highest solid particle residence time and the quickest solid particle temperature rise. Although a rapid solid particle temperature rise is desirable, it is critical to avoid stagnant regions or jamming that may occur for slow moving solid particle flows.

Table 3. DEM simulation key parameters and results for varying with inclination angle

Inclination Angle (°)	10	20	30
Inlet Solid Particle Mass Flux (kg/m²-s)	39	65	91
Total Solid Particle Mass Flow Rate (kg/s)	0.0045	0.0139	0.0168
Solid Particle Temperature Rise (°C/m)	1757	851	561
Residence Time on One Heating Element (s)	0.0634-0.127	0.0443-0.0998	0.0433-0.0866

These simulations reveal that solid particle 102 residence time is important for maximizing the temperature rise of the solid particles 102 in a particle heater 150. The solid particle 102 residence time is defined as the length of one heating element 180 divided by the minimum and maximum solid particle velocity across one heating element 180. At lower (i.e., shallower) inclination angles, the residence time increases and results in period of thermal contact between the solid particles 102 and the surface 183, resulting in adequate temperature rise. To assess the tradeoff between residence time and potential flowability issues (e.g., jamming), a friction coefficient was parametrically studied. In some embodiments, the inclination angle may be in the range of about 5° to about 75°. Friction was investigated because the solid particle flow properties are critical to the solid particle heat transfer process. It is possible that friction may reduce the residence time, and increase heat transfer, but the resultant flowability of the solid particles 102 may be a concern. The solid particle-solid particle and solid particle-surface friction coefficient, μ , evaluated were zero (0), 0.15, and 0.30.

Figure 8 shows that friction may impede the flow on the top row (i.e., slower velocity in the top row of the case with friction applied versus exact same case with no friction applied), but this change in impedance does not appear in subsequent rows of heating elements 180. Figure 8 shows the same heater geometry and inlet conditions, but the left has no friction, and the right has a solid particle-solid particle and solid particle-surface friction coefficient of 0.15. As the friction increased, the solid particle flow through the initial row of heating elements 180 became restricted and the subsequent flow through the lower heating elements 180 became more dilute. Figure 9 shows the difference in gas fraction between simulations with varying friction coefficients. As described above, in some embodiments of the present disclosure, the shape of a heating element 180 may have a cross-sectional shape 183 of a substantially hexagonal shape to enhance the solid particle-surface contact and solid particle-solid particle mixing. The shape and size of the heating elements 180, as well as the layout of the heating elements 180 control the solid particle flow, heat transfer, and heating load. In some embodiments of the present disclosure, a solid particle-surface heat transfer coefficient of about $500 \text{ W/m}^2 \text{ K}$ may be targeted. A high heat transfer coefficient is important because it is necessary to ensure the solid particles cool the heating elements 180 effectively in order to enable high power output.

As previously discussed, to efficiently obtain results from DEM, the simulations were limited to relatively small-scale simulations. A reduced order analytical model was developed and approximations for the heat transfer coefficient were obtained from discrete heating element 180 simulations. The analytical model was verified by comparing the analytical temperature profile and predicted product height for both a small-scale (i.e., a particle heater 150 of about 23.5 cm in height) and a medium-scale simulation (i.e., a particle heater 150 of about 47 cm in height). This predicted product height is defined as the height at which, based on the analytical model, the solid particles reach a target temperature of approximately $1,200 \text{ }^\circ\text{C}$. In some embodiments, the target temperature may be between about $1000 \text{ }^\circ\text{C}$ and $1300 \text{ }^\circ\text{C}$. Figure 10 shows the simulation results for comparison.

As can be seen, the analytical temperature profiles and predicted heights closely match. The analytical model is based on DEM simulation results, so there was no adjusting of parameters to make the profiles match; it happened naturally. Since the analytical profiles both followed the DEM results and matched between a small and medium simulation, the analytical model was verified. This validates that the model could be used to expand from small-scale results to the

large-scale design considerations. Some large-scale results resulting from the analytical model being used to model solid particles temperatures over much larger heights are shown in Figure 11.

The heating elements 180 are the smallest units that convert electric power into thermal energy thereby heating the solid particles 102 in a particle heater 150. Thus, among other things, the size and shape of the heating elements 180 may determine solid particle flow and heat transfer and are the important design parameters in modeling, testing, and optimizing a particle heater 150 design. In some embodiments of the present disclosure, a wire-wrapped heating element 180 may be used (as shown in Figure 4). Among other things, this design makes it easy to change shape and size compared to other heating element 180 designs such as molded ceramic or silicon carbide (SiC) heating elements 180 that may also be used in commercial-scale units. To achieve mass production, low-cost and highly reliable product heating elements 180 can incorporate other high-temperature resistor heaters. In some embodiments, the heating elements 180 can directly use refractory materials as a resistor heater, which can simplify the particle heater 150 design and eliminate the need for a heating wire (shown as wire 194 in Figure 12). A backing material may support wires in the shape of rods that are capable of very high temperatures (e.g., to 1,600 °C). Some refractory materials have been tested for their compatibility with silica solid particles. Features of exemplary heating elements are shown in Figure 12.

Candidate materials for the heating element 180 resistive heater components include nickel-chromium (NiCr) wires or bars, Kanthal or iron-chromium-aluminum (FeCrAl) wires or bars, SiC wires or bars, and Molybdenum Disilicide (MoSi₂) wire or bars. Factors considered when selecting materials of construction for heating wires include usable temperature ranges, atmosphere conditions, life, power, and heat load requirements.

- *FeCrAl*

- Maximum temperature approximately 1,400 °C
- Inexpensive, rugged (mechanical/thermal shock)
- Little problem with thermal cycling
 - Lower hot strength, reduced ductility, and embrittlement with use.
- Wire, strip, rod (i.e., bar) forms

- *SiC*

- Maximum temperature approximately 1,700 °C, relatively low power (W/cm²)

- ***MoSi₂*** (Molybdenum Disilicide)

- Maximum temperature approximately 1,800 °C, relatively high power (W/cm²)

Other factors to consider when selecting heating wire materials include:

- For long life, low head temperature (so lower Watt loading) with respect to furnace temperature. This requires more elements in furnace (and thus, takes more space).
- Heater power load is limited by the allowable temperatures.
- Furnace process temperature is often limited by furnace wall material

Table 4 lists potential candidates that may be used as resister heater materials (for use as or in conjunction with heating elements 180) to heat solid particles 102 above 1,200 °C.

Table 4. Candidates of resistance heating materials

	Material	Maximum heating capacity (W/cm ²)	Max usable temperature in air (°C)
NiCr wire	NiCr	9	1,200
FeCrAl wire	FeCrAl	11	1,400
SiC heater	SiC	14	1,700
Molybdenum Disilicide	MoSi ₂	30	1,800

There are at least two designs for electrical resistance heating of the solid particles 102. As mentioned, one design is to have heating elements 180 constructed of heating wires (FeCrAl wire) wrapped around a refractory bar in the desired cross-sectional shape 183 to obtain the solid particle flow and heat transfer in the charging particle heater 150. Another design uses the heating elements 180 themselves to provide the thermal energy (e.g., electrical current would run through the heating element 180 itself, not a wire wrapped around the heating element 180). Ceramic and SiC heating elements 180 can be prefabricated with specific shapes that are likely only suitable for mass production, because special shaped mold may need to be used for large production scale. Scaling up a particle heater 150 to the large quantities that may be needed for full-scale operations may support various shape requirements while maintain a reasonable cost. In some embodiments of the present disclosure, a design for a high-performance heating element 180 may include MoSi₂ heating strips attached to refractory backing rods (i.e., support 189 as shown in Figure 1D). MoSi₂ has superior high-temperature capabilities and high-heat flux values. Thus, among other materials, MoSi₂ can meet the high heating rate requirements anticipated for solid particle heat transfer.

As described herein, heating wires can provide electric resistance heating to the heating elements 180 contained in a particle heater 150, thereby raising the temperature of the solid particles 102 passing through the particle heater 150. In some embodiments of the present disclosure, a heating wire may wrap around a refractory backing support and to terminate on a metal block at a desirable temperature condition. A metal terminal block may link to an electric bus bar that may also support a heater module of a particle heater 150. The support bus bar may be placed inside the heater chamber at temperature below 350 °C, the cold solid particle inlet temperature.

To achieve low-cost and high reliability, heating elements 180 may be different from a prototype particle heater 150 for the following reason:

1. A prototype particle heater 150 is easily fabricated in small quantities and is a good starting point for particle heater 150 characterization.
2. Wire in contact with solid particles may have a life-span issues.
3. A concept of a firebrick resistance heater that directly uses refractory material as a resistor heater may be used, which simplifies the heater design and minimizes failure due to fire.
4. A product particle heater 150 may use other ceramics or refractory material with appropriate dielectric properties and manufacturability.

As describe above, a particle heater 150 may be designed in a modular configuration with fixed power and solid particle flow rates for each heater module 155 making up the particle heater 150. A solid particle flow rate may be predetermined by the heating element 180 shape, size, and arrangement. This results in a solid particle flow control strategy that avoids using variable valves or any moving parts operating under extremely high temperature conditions. Since the flow control strategy described herein only needs on/off states for each heater module 155, the solid particle flow control valve may simply use gate valves 175 located in the solid particle distributors and/or flow passages directing solid particles to each individual heater module. Among other things, this solid particle flow control design reduces particle heater 150 cost and improves the operating reliability. Such features are illustrated in Figure 13, according to some embodiments of the present disclosure.

Figure 14 illustrates a single heater module 155 that is contained in a housing 160, according to some embodiments of the present disclosure. A heater module 155 houses numerous individual heating elements 180 that are in direct contact with solid particles 102 in order to heat the solid

particles 102. As mentioned, a heater module 155 is designed with fixed solid particle flow and heating capacity. A single heater module 155 can be operated only in on or off states with the number of heater modules 155 on varying according to the charging load. The enclosure of each heater module 155 may be internally insulated to keep the temperature of the interior of the housing 5 160 outside of the heater modules 155 below 300 °C. The housing 160 layers may be made of refractory, calcium silicate, and/or mineral wool to, among other things, protect the steel rail, electric connectors, and structure. The entirety of each heater module 155 may be mounted on rollers connected to a support 177 (such as an I-beam) for easy removal and maintenance.

A particle heater 150 may be powered using grid alternating current (AC) power after converting 10 to the required heating wire input voltage. The maximum particle heater 150 operating temperature and the solid particle exit temperature will be monitored for safety and to ensure the particle heater 150 is achieving the set point operating temperature (e.g., about 1,200 °C). A full-scale particle heater 150, including power supply, will use the most up to date industry standards for production cost and service life. In some embodiments of the present disclosure, each heater module 155 may 15 be integrated into an overall particle heater 150 by mounting the heater modules 155 below a particle distributor 165 that receives the relatively cold solid particles that have been discharged from the particle heater 150 used to convert the thermal energy stored in the solid particles 102 back to electricity (e.g., using a pressurized fluidized bed heat exchanger). The heater modules 155 may then connect to a particle collector 170 (i.e., bottom hopper) that distributes the heated solid 20 particles 102 to a designated thermal energy storage silo 101 to be held until required for electricity generation.

In some embodiments of the present disclosure, a heater module 155 may not of itself provide solid particle flow control other than by the resistance to solid particle flow provided by the heating elements 180 themselves contained within the heater module 155. Flow to a particular heater 25 module 155 will be either on or off depending on the position of the corresponding gate valve 175 controlling the flow to a particular heater module 155.

Heater modules 155 may be integrated into a complete particle heater 150 that provides solid particle flow control to each individual heater module 155 (e.g., using gate valves 175), as well electrical connections to the power lines connecting to the electrical grid. Heated solid particles 30 102 may collect in the particle distributor 165 and to be dispensed by corresponding gate valves

175 operating at the targeted high target temperature (e.g., 1,200 °C). Heater modules 155 may be supported by an I-beam and/or steel rail that may also conduct electricity from the electrical power supply to the heater modules 155. A heater module 155 may slide on the rail and to be moved out of the particle heater 150 for maintenance.

- 5 In addition, using ANSYS Mechanical, a finite element analysis (FEA) solver, a steady-state thermal model was built to study the potential insulation 185 requirements of an individual heater module 155. The geometry used represented a 1.0 m² square solid particle 102 inlet area and 2.0 m height of the heater module 155; as this is a general case, design changes were easily accommodated, and new results quickly produced and analyzed. For computational efficiency, the
- 10 geometry was sliced into a quarter along the center lines of symmetry, as shown in Figure 15. In this example, a cast refractory layer, composed of Petromax® 550 by Allied Mineral, was used as the most interior insulation 185 material due to its high thermal limit and mechanical strength. However, the resultant particle heater 150 may potentially be extremely heavy, costly, and significantly larger if refractory was the sole insulator utilized. Therefore, a design decision was
- 15 made to cast the refractory material with supporting rods of the same material to connect to the outer steel shell to maintain the structural integrity of the particle heater 150. The remaining volume would be filled with a cheaper, less dense insulation material, such as, for example, calcium silicate (CaSi) and/or mineral wool, which were both chosen as candidates in this study. With the geometry established, several insulation designs were evaluated. Each insulation 185
- 20 design was evaluated over a range of convective heat transfer coefficients ranging from 1.0-10.0 W/m²-K to simulate natural and forced convection conditions. The ambient temperature was fixed for this convection was fixed at 300 °C because individual heater modules 155 may be contained in a larger container (i.e., housing 160), in addition to the complete particle heater 150 being insulated further to protect from the environmental weather conditions.
- 25 To simulate the solid particles heating along the length of a heater module 155, a 1D temperature profile was applied to the exposed refractory surface. An applied temperature profile instead of a convective heat transfer boundary condition was applied due to the high solid particle-surface heat transfer coefficients expected; this means the temperature gradient between the surface and ambient solid particle domain will likely be relatively small. Two temperature profiles were
- 30 implemented, linear and exponential, to simulate different potential heating scenarios. Regardless of the profile shape, both profiles raised the solid particle temperature from about 300 °C to about

1,200 °C from inlet (top) to outlet (bottom) of the particle heater 150. Figure 16 contains a visual representation of the boundary conditions as well as the insulation thickness parameters (t_r , t_{i1} , and t_{i2}) that were varied to produce different insulation 185 designs. Three designs were chosen to be reported here and their associated insulation 185 dimensions are shown in Table 5. Table 5 presents three insulation designs selected. The volumes for the refractory and insulation of a full single heater, V_r and V_i , respectively, and the associated total insulation material (refractory + CaSi) cost for a full-size single heater module. In some embodiments, the heater module 155 may have a diameter in the range of about 0.1 m to about 10 m and a height in the range of about 0.1 m to about 10 m. For example, in some embodiments, the heater module 155 may have a diameter of less than 1 m and a height of less than 4 m.

Table 5. Insulation designs and associated thickness and volume.

Design No.	t_r (m)	t_{i1} (m)	t_{i2} (m)	V_r (m ³)	V_i (m ³)
1	0.1	0.0	0.5	1.08	2.88
2	0.2	0.1	0.5	2.16	3.96
3	0.2	0.1	0.3	2.08	2.44

The choice of insulation 185 material indicates that a configuration resembling Design #3 in Table 5 strikes a balance between performance and cost. Design #3 is cheaper than both designs while meeting temperature constraints of the CaSi utilized and reducing the average exterior temperature of the steel shell to reasonable temperatures near 300 °C. Therefore, around 0.5 m of insulation 185 at the thickest point ($t_r + t_{i2}$) should be expected to achieve sufficient insulation between the interior and exterior of the heater; this is valuable knowledge going forward for the heater component design.

A summary of some of the key benefits offered by the electric particle heater 150 designs described herein include:

- 1) Particle heater 150 layout, including multiple heater modules 155 in particle heater 150 assembly allows for:
 - a) Movable (both entire particle heater 150 and the heater modules 155)
 - b) Fixed load and solid particle flow in each heater module 155
 - c) Solid particle dispensing and collecting through dispenser 165 and collector 170
- 2) Modular design
 - a) Flow control of solid particles through the particle heater 150
 - b) Electric connection to heating elements 180
 - c) Support structure to support and possibly connect the heater modules 155
- 3) Heating elements 180 assembly and support,
 - a) Heating elements 180 have unique cross-sectional shape 183 for maximum solid particle flow through the particle heater 150
 - b) Tube shape and arrangement for solid particle heating

The foregoing discussion and examples have been presented for purposes of illustration and description. The foregoing is not intended to limit the aspects, embodiments, or configurations to the form or forms disclosed herein. In the foregoing Detailed Description for example, various features of the aspects, embodiments, or configurations are grouped together in one or more embodiments, configurations, or aspects for the purpose of streamlining the disclosure. The features of the aspects, embodiments, or configurations may be combined in alternate aspects, embodiments, or configurations other than those discussed above. This method of disclosure is not to be interpreted as reflecting an intention that the aspects, embodiments, or configurations require more features than are expressly recited in each claim. Rather, as the following claims reflect, inventive aspects lie in less than all features of a single foregoing disclosed embodiment, configuration, or aspect. While certain aspects of conventional technology have been discussed to facilitate disclosure of some embodiments of the present invention, the Applicants in no way disclaim these technical aspects, and it is contemplated that the claimed invention may encompass one or more of the conventional technical aspects discussed herein. Thus, the following claims are hereby incorporated into this Detailed Description, with each claim standing on its own as a separate aspect, embodiment, or configuration.

CLAIMS

What is claimed is:

1. A heater for heating a plurality of solid particles, the heater comprising:
at least two three-dimensional (3D) shapes, each 3D shape comprising at least two
5 surfaces; wherein:
each surface of each 3D shape comprises at least two lateral edges positioned
substantially parallel to a first axis (z), each lateral edge has a length between a proximal end and
a distal end,
each surface comprises a proximal edge positioned at the proximal end of the length
10 and within a first plane defined by a second axis (x) and a third axis (y),
the proximal edges of each surface of each 3D shape form a cross-sectional shape
in the plane,
at least one surface of each 3D shape is positioned to face at least one surface of
another 3D shape defining a channel,
15 the channel is oriented to enable the gravitational flow of the plurality of solid
particles through the channel,
at least one surface defining the channel is configured to transfer heat to at least a
portion of the plurality of solid particles,
x and y are each perpendicular to z, and
20 x and y are perpendicular to each other.
2. The heater of claim 1, wherein:
the at least one surface defining the channel is configured to operate at a
temperature between about 500 °C to about 1500 °C.
- 25 3. The heater of claim 1, wherein the cross-sectional shape is a polygon.
4. The heater of claim 3, wherein:
the polygon has an interior angle defined as the angle between x and a proximal
30 edge, and
the interior angle is in the range of about 5° to about 60°.

5. The heater of claim 4, wherein the interior angle is approximately 10° .

6. The heater of claim 3, wherein the polygon is a triangle, a quadrilateral, a pentagon,
5 a hexagon, a heptagon, an octagon, a nonagon, or a decagon.

7. The heater of claim 1, wherein:
the at least one surface defining the channel configured to transfer heat comprises
a resistive heating element.

10

8. The heater of claim 7, wherein the resistive heating element is positioned within an
indentation in the at least one surface defining the channel.

9. The heater of claim 6, wherein the resistive heating element comprises an electric-
15 resisting wire or bar.

10. The heater of claim 1, wherein:
the channel has a width substantially parallel with x.

20 11. The heater of claim 10, wherein:
the width is in the range of about 0.05 m to about 1.5 m.

12. The heater of claim 11, further comprising:
a block positioned between the at least two 3D shapes and filling at least a portion
25 of the channel, wherein:
the block is configured to maintain the width of the channel.

13. The heater of claim 12, wherein:
the block is further configured to direct the plurality of solid particles towards the
30 at least one surface defining the channel configured to transfer heat

14. A particle heater configured to heat a plurality of solid particles, the particle heater comprising:

a heater module having an inlet and an outlet and substantially filled with a plurality of heating elements which define a plurality of channels, wherein:

5 the plurality of heating elements are configured to direct the plurality of solid particles through the plurality of channels,

the plurality of heating elements are configured to receive electrical energy to generate heat resulting in heating of the plurality of solid particles from a temperature at the inlet between about 250 °C and about 500 °C to a temperature at the outlet between about 850 °C and
10 about 1,200 °C.

15. A method of heating a plurality of solid particles, the method comprising:

receiving the plurality of solid particles to an inlet of a heater module substantially filled with a plurality of heating elements which define a plurality of channels;

15 directing the plurality of solid particles through the plurality of channels;

heating the plurality of solid particles from a temperature at the inlet between about 250 °C and about 500 °C to a temperature at an outlet of the heater module between about 850 °C and about 1,200 °C using the plurality of heating elements; and

20 removing the plurality of solid particles from the heater module via the outlet;
wherein:

the plurality of heating elements are configured to receive an electrical energy and convert the electrical energy to a thermal energy for the heating.

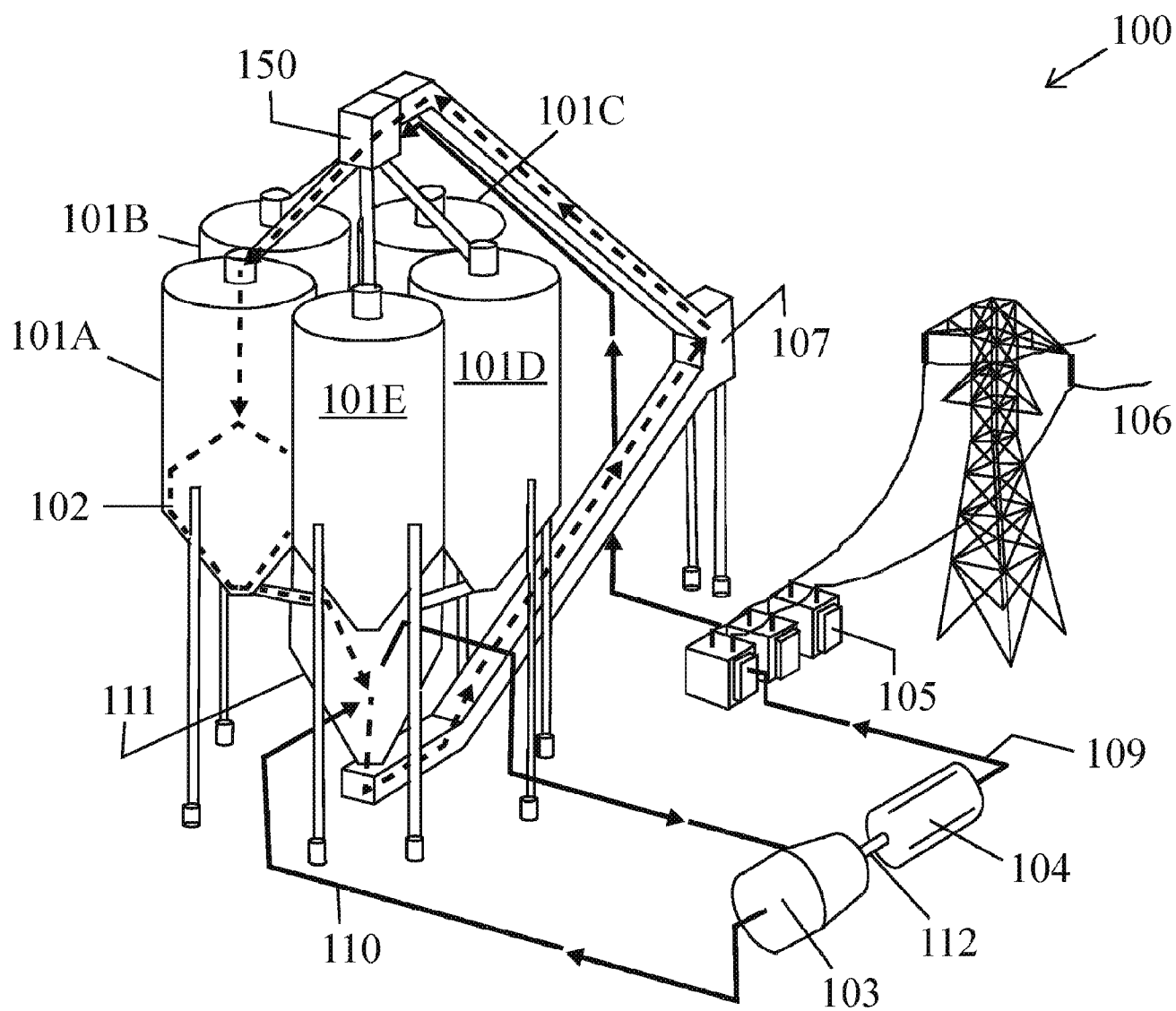


Figure 1A

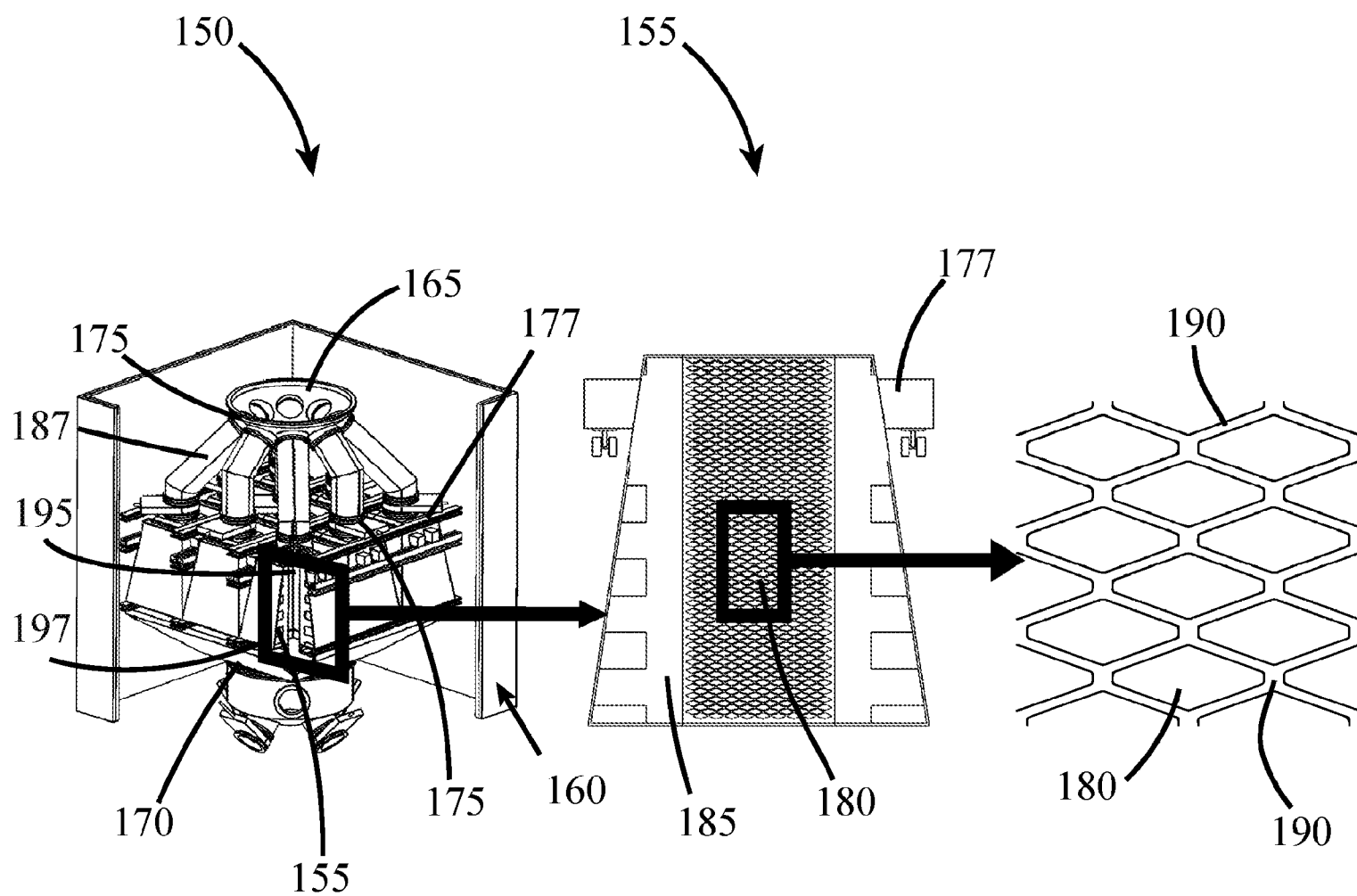


Figure 1B

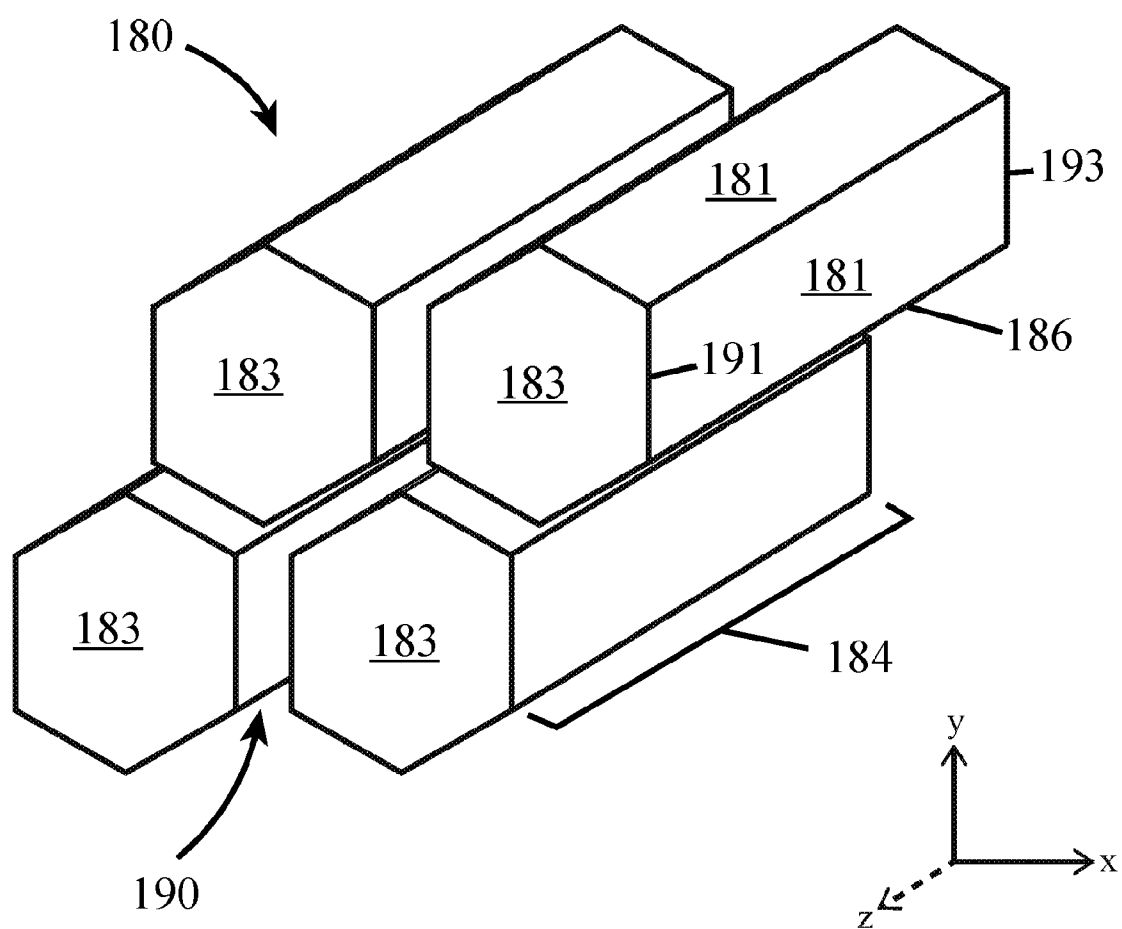


Figure 1C

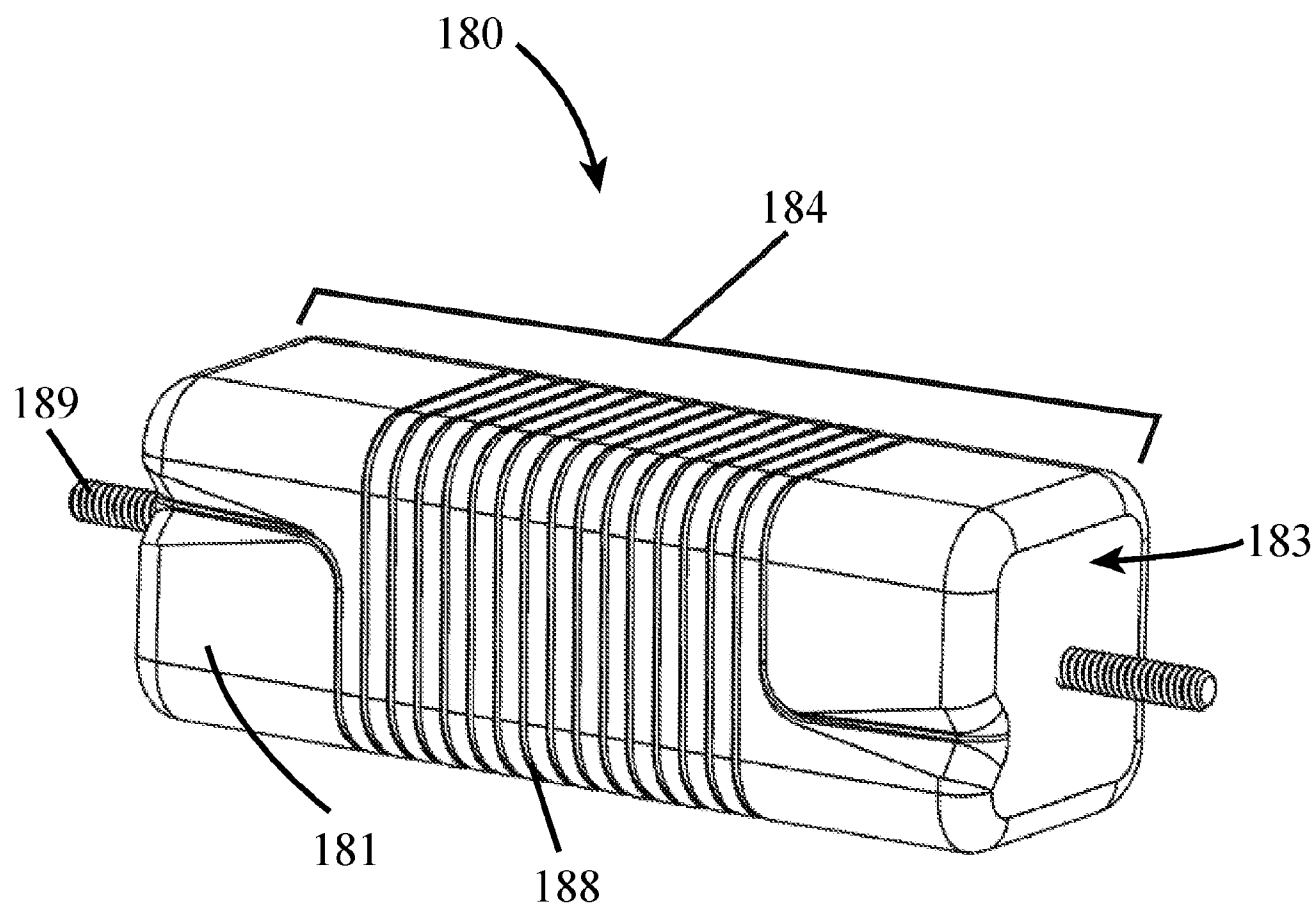


Figure 1D

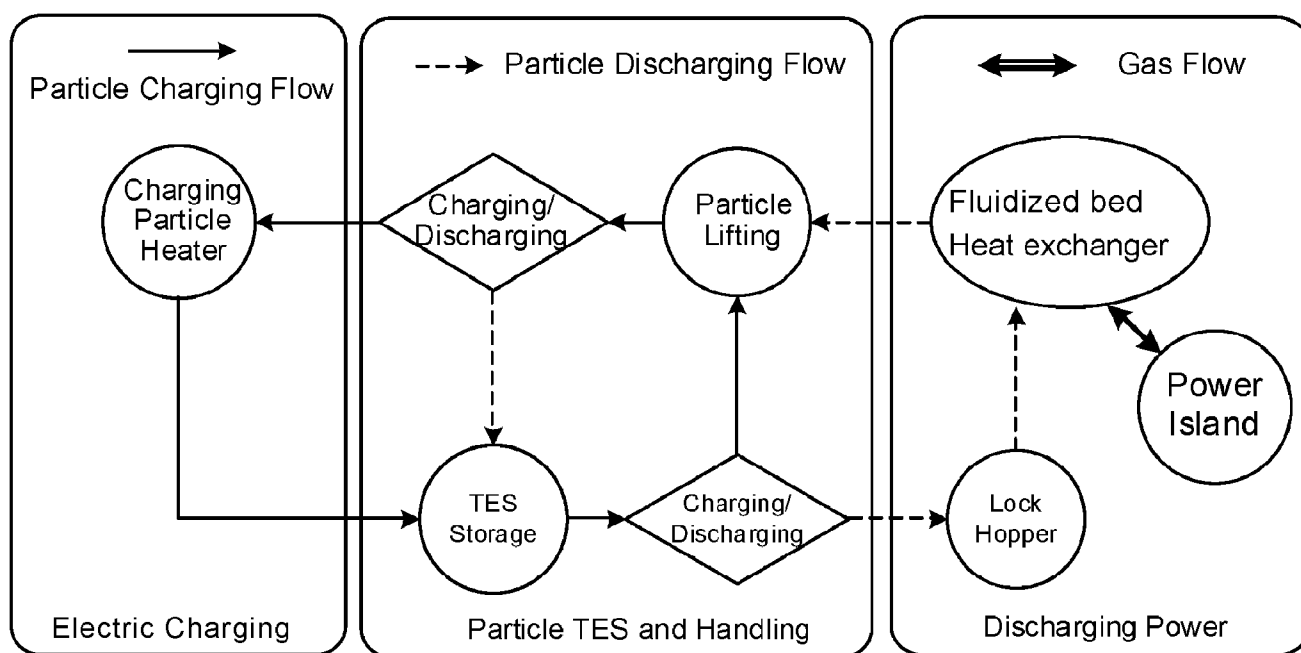


Figure 2

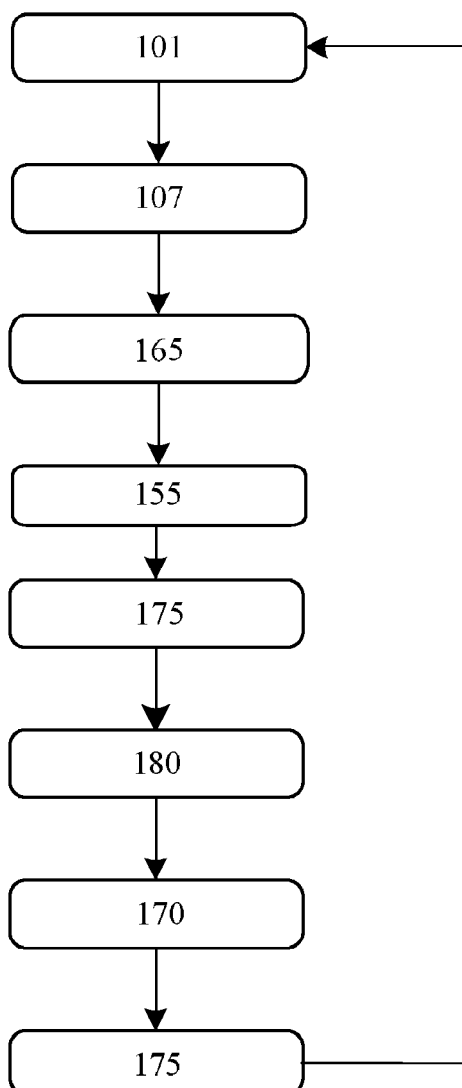


Figure 3

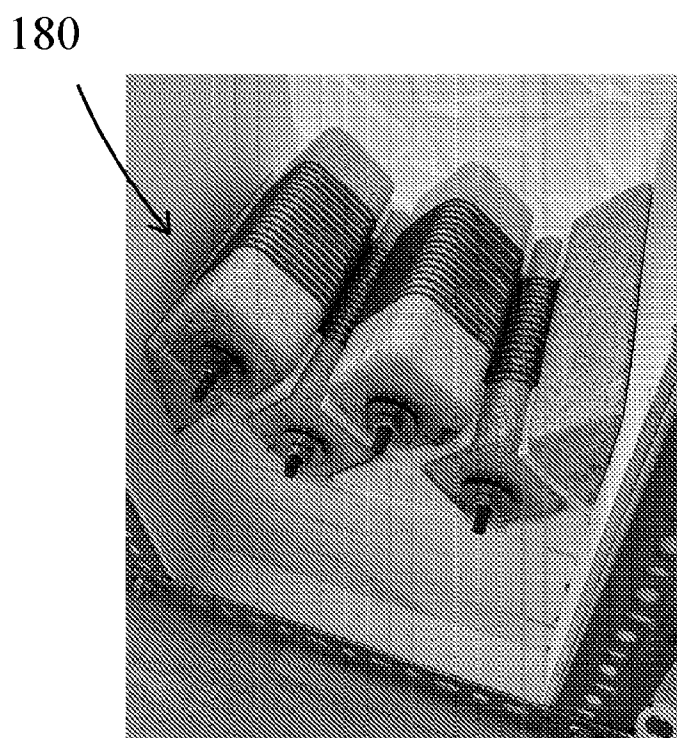
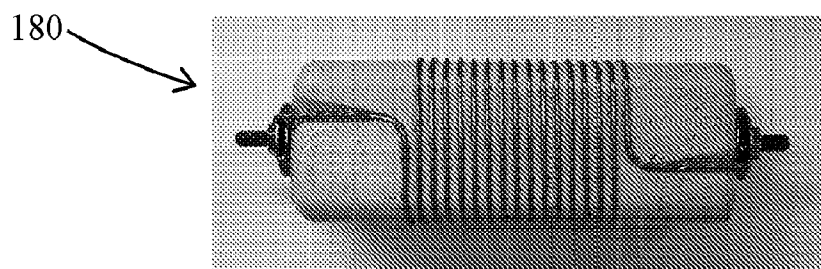


Figure 4

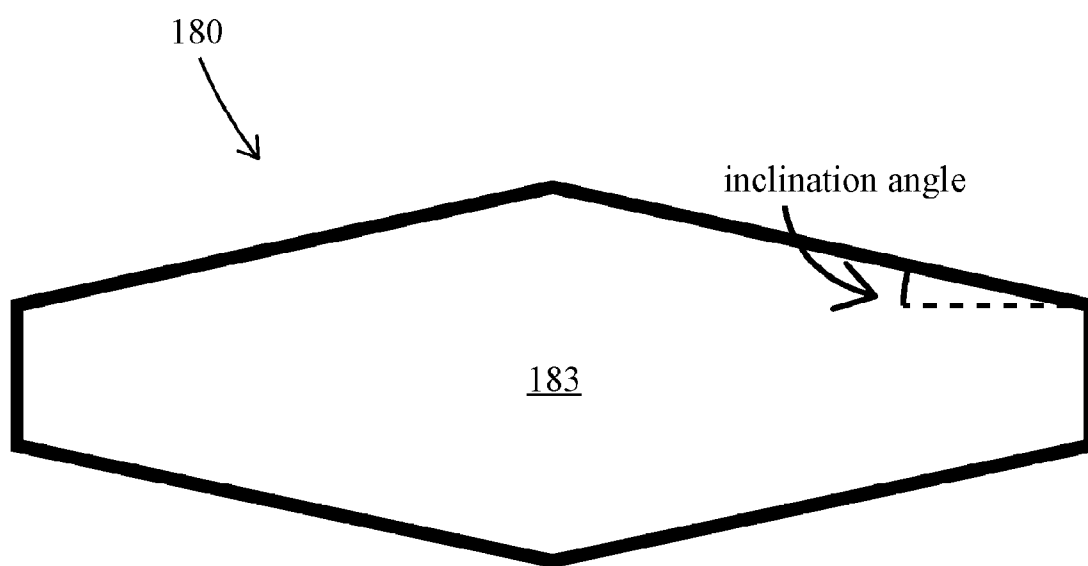


Figure 5

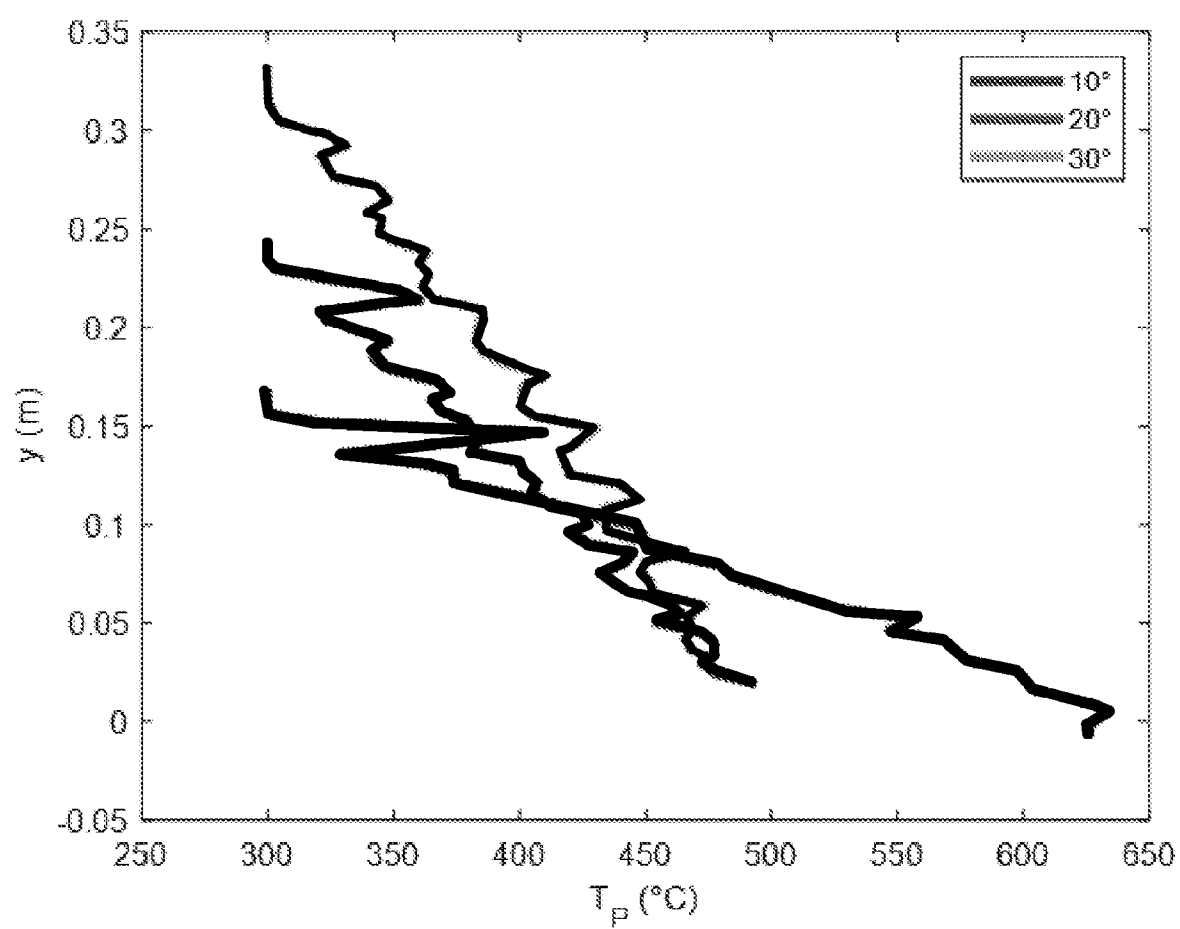


Figure 6

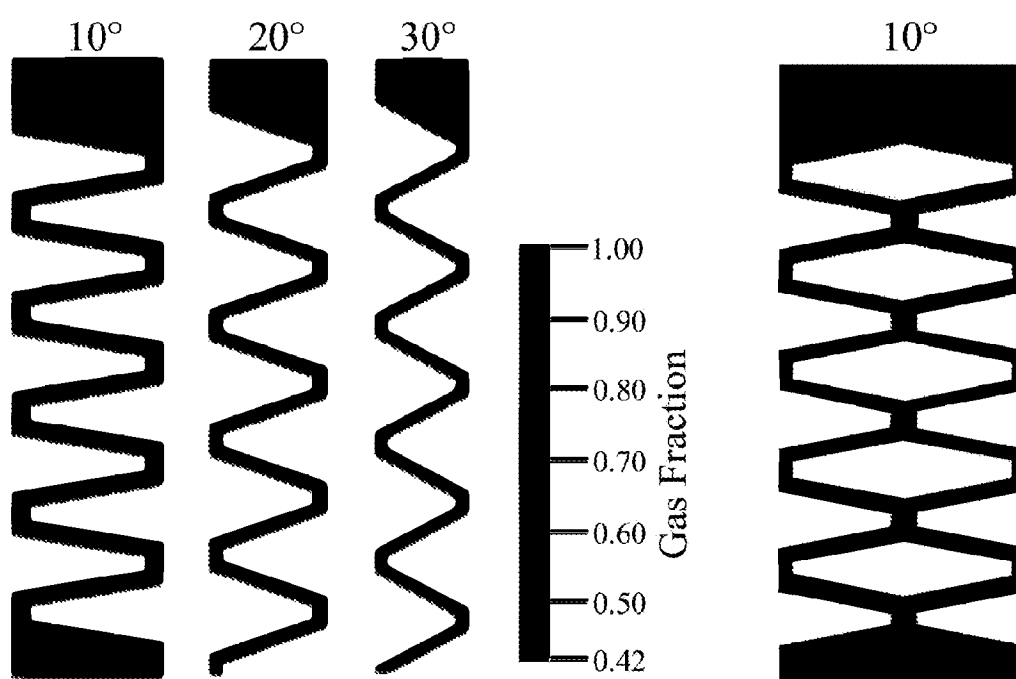


Figure 7

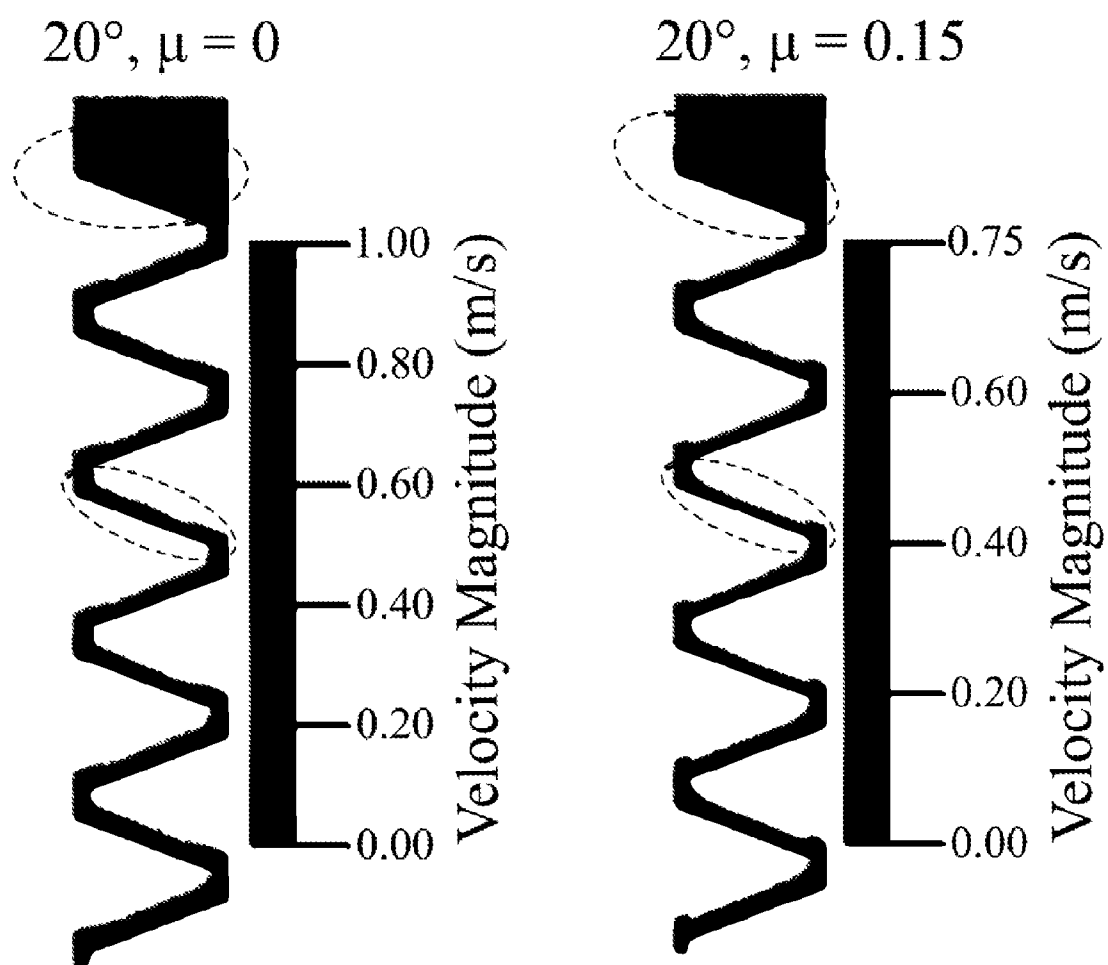


Figure 8

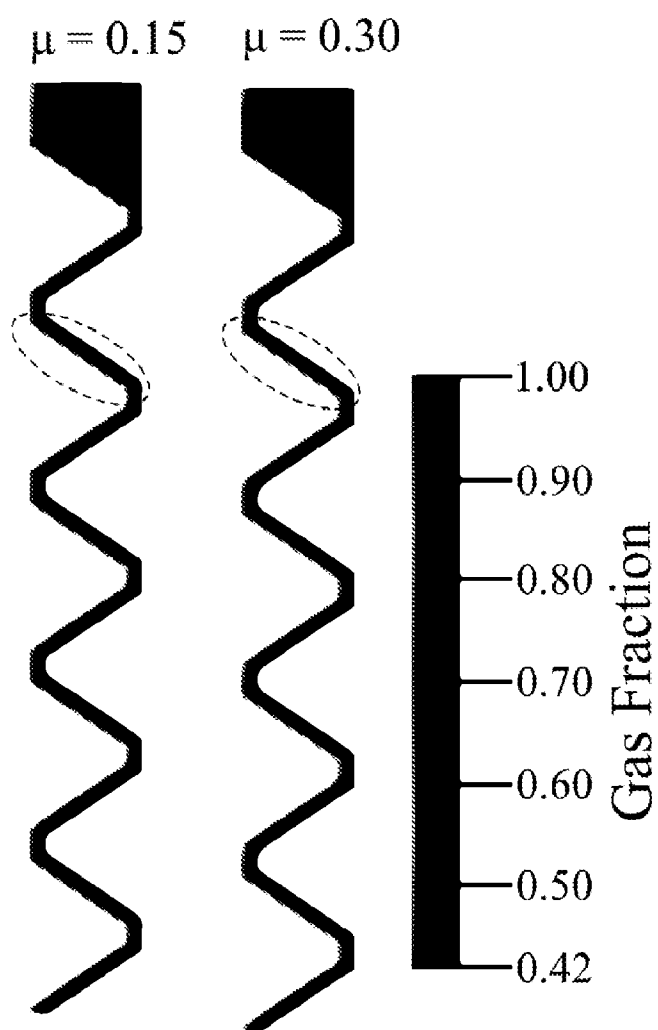


Figure 9

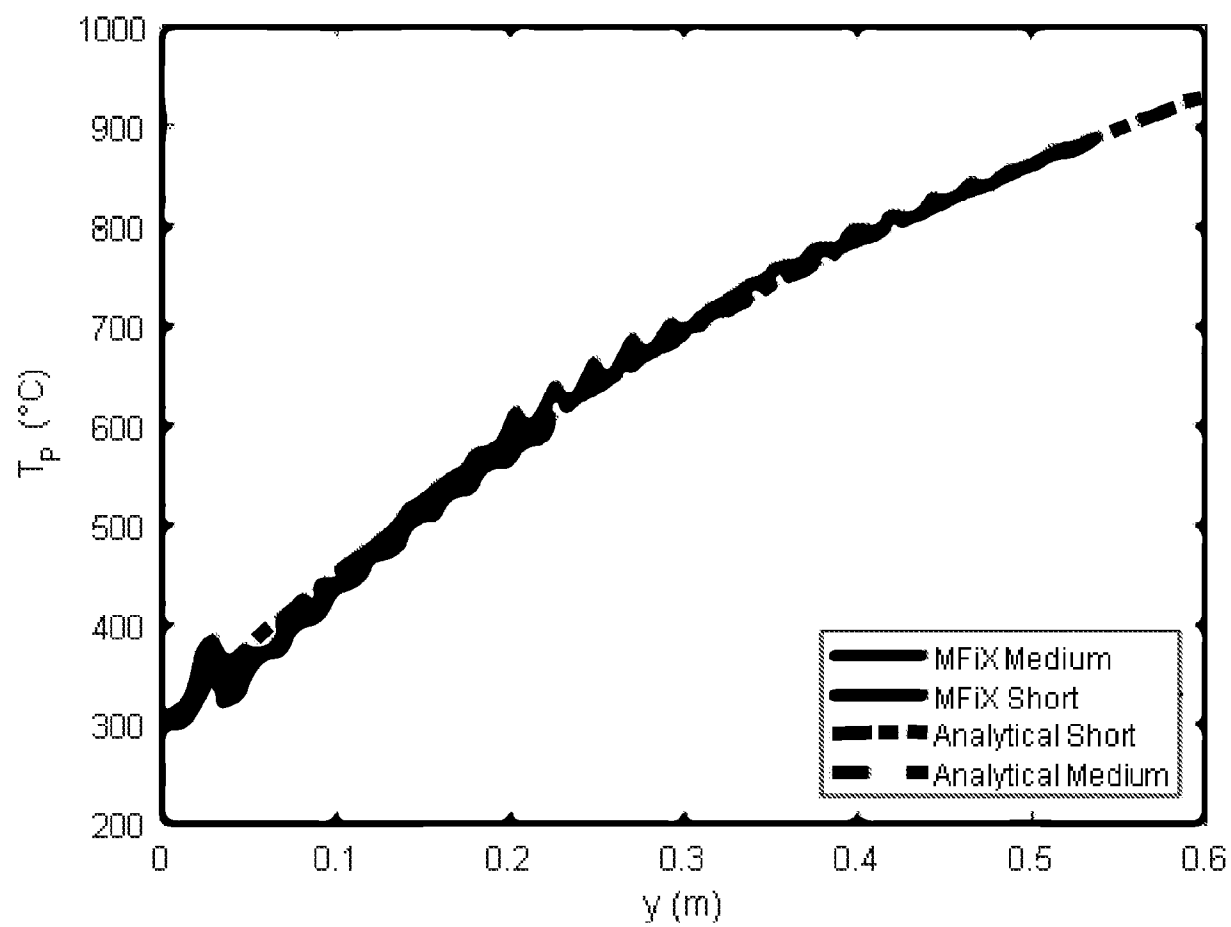


Figure 10

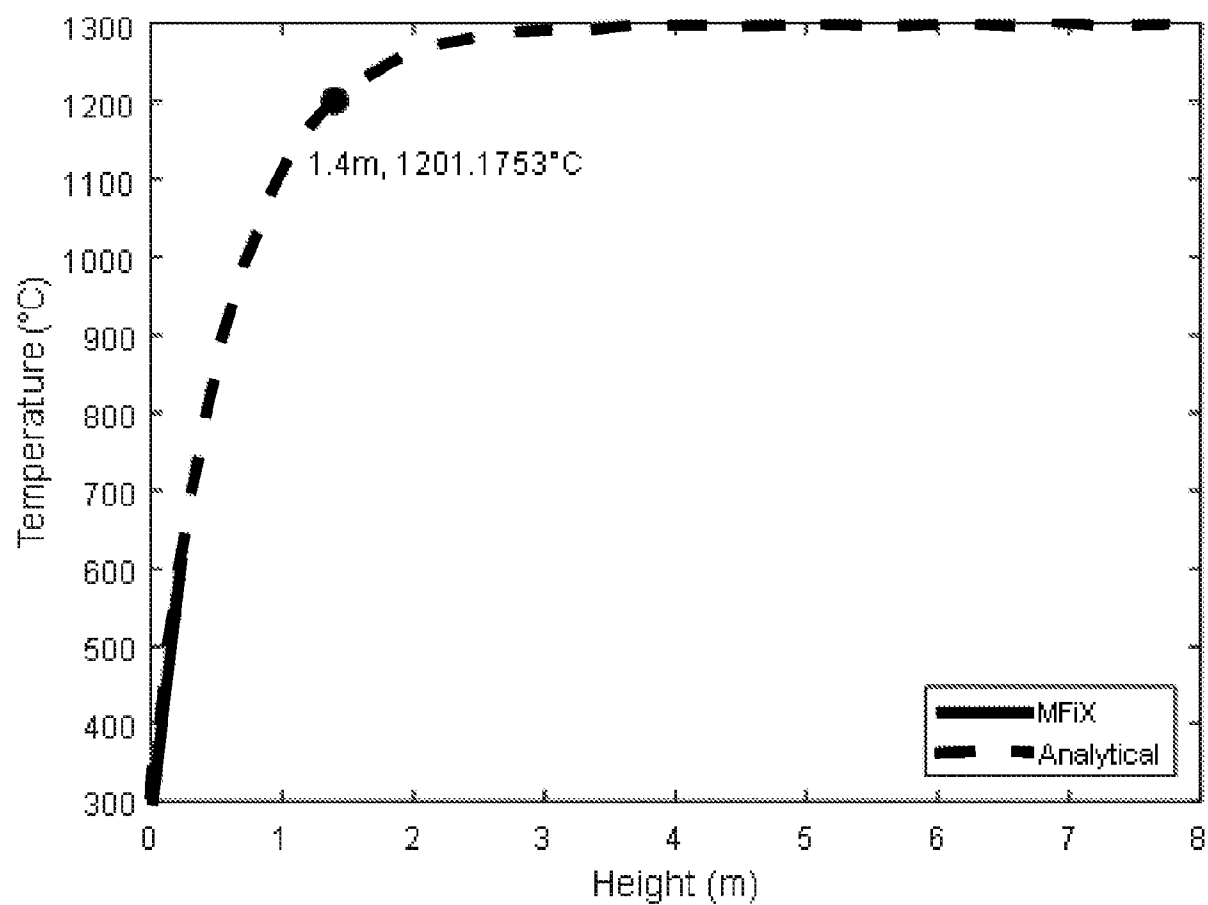


Figure 11

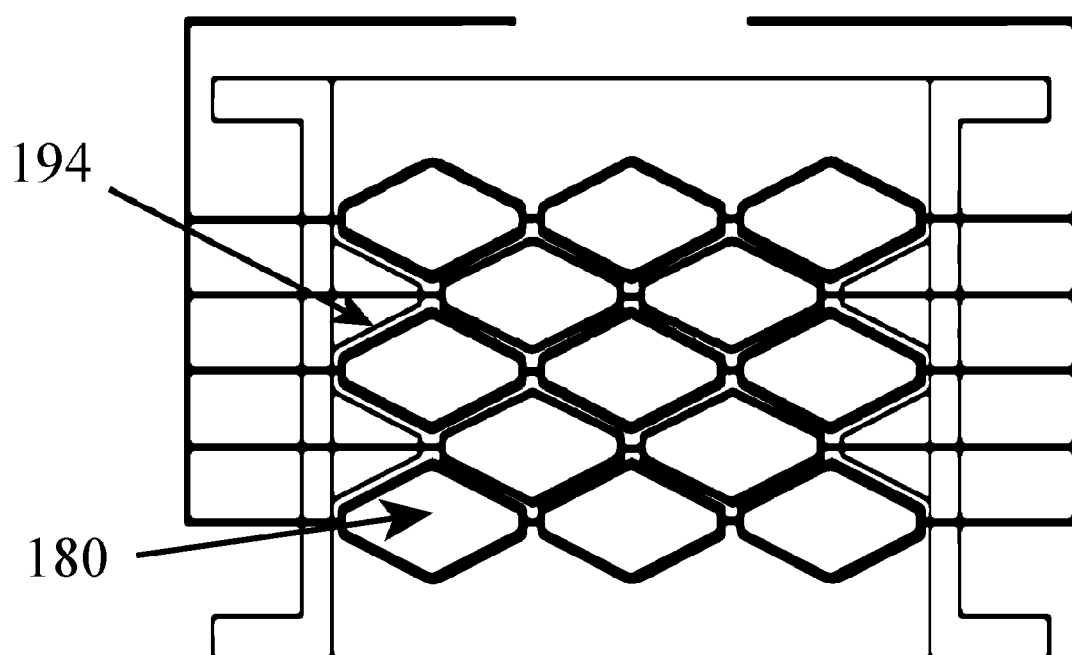


Figure 12

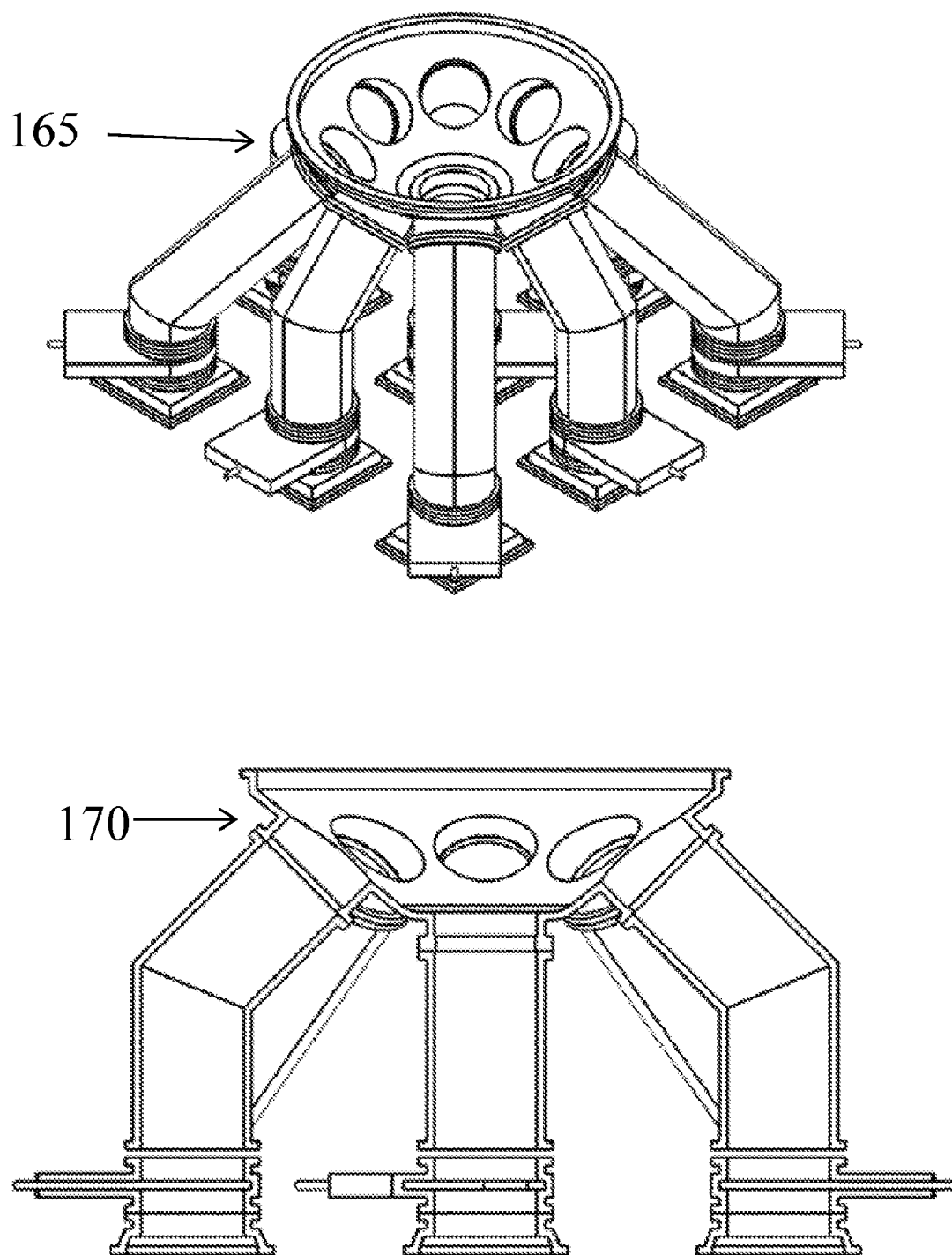


Figure 13

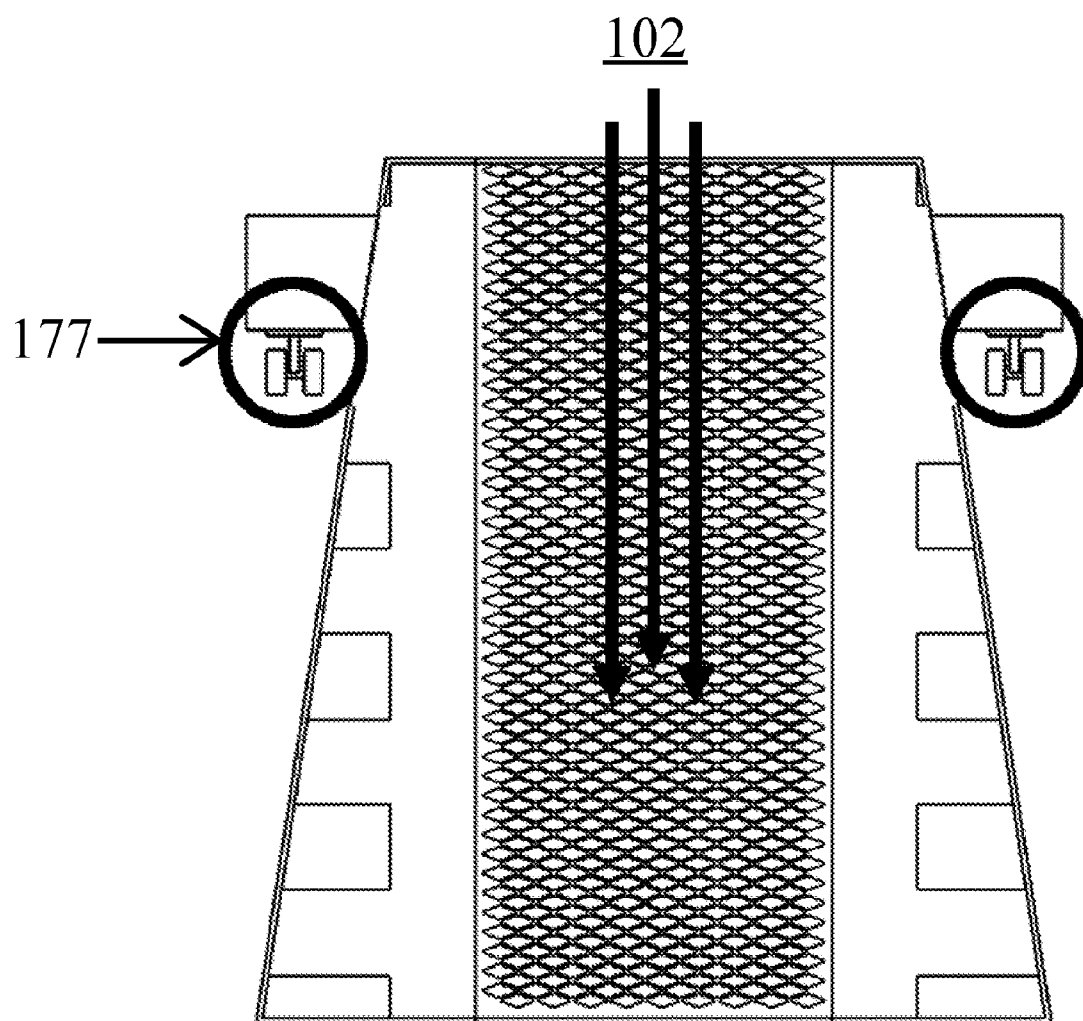


Figure 14

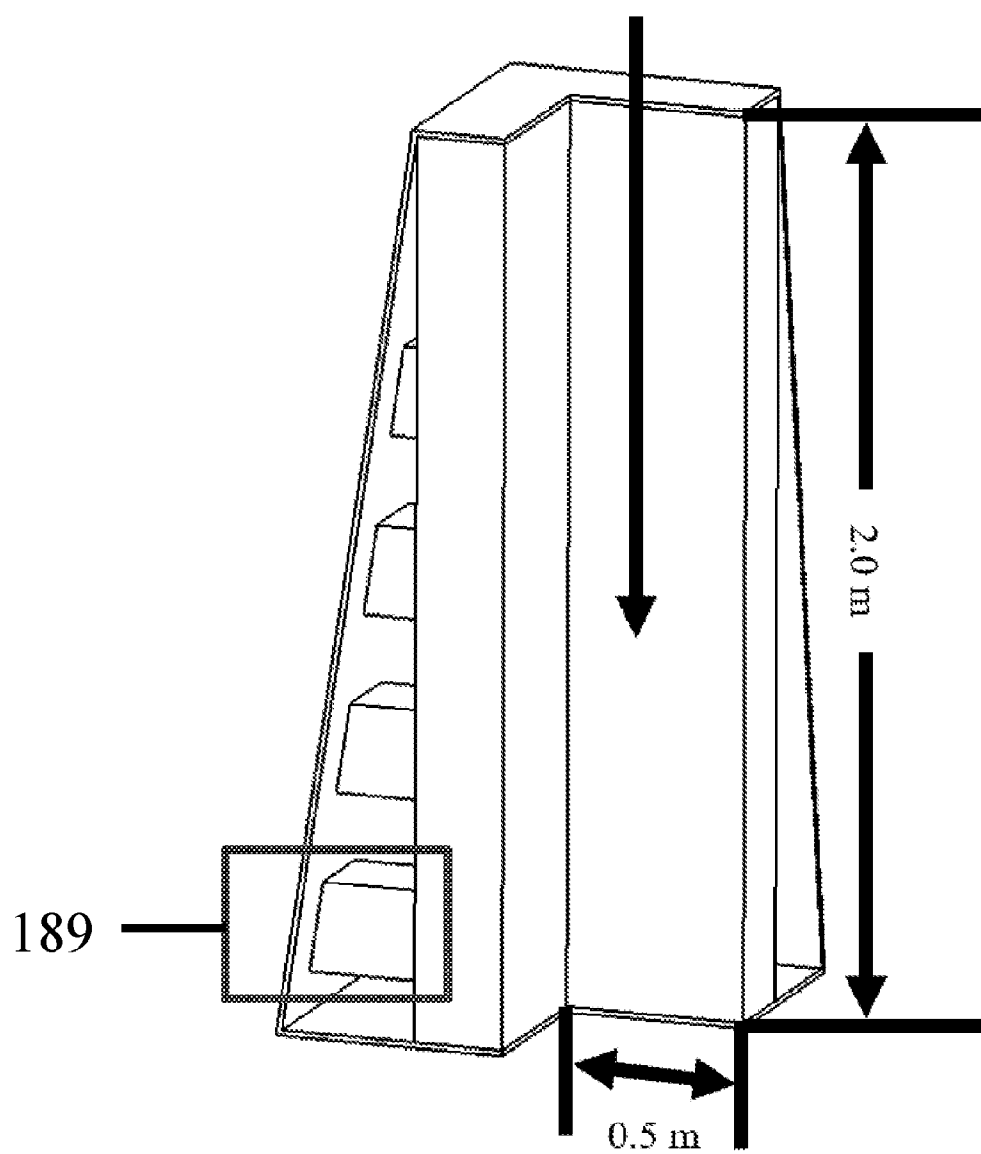


Figure 15

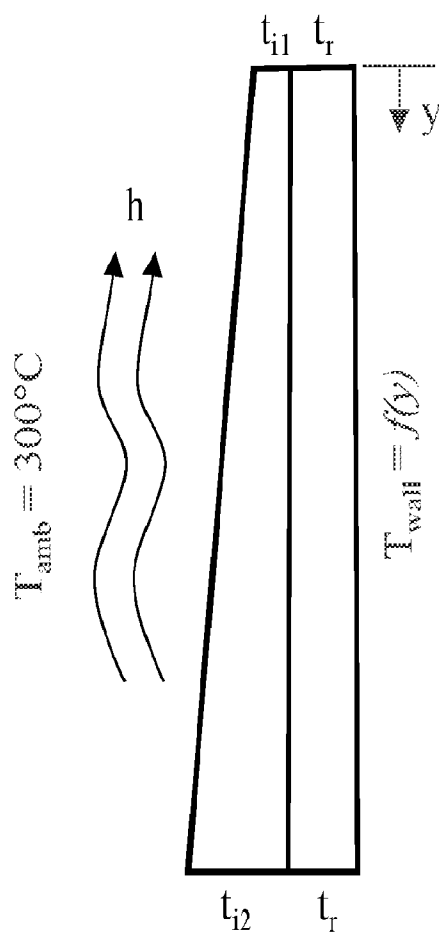


Figure 16

Date Submitted: 2023/01/11

CA App. No.: 3185600

Abstract:

The present disclosure describes heat exchangers for converting thermal energy stored in solid particles to electricity. Electro-thermal energy storage converts off-peak electricity into heat for thermal energy storage, which may be converted back to electricity, for example during peak-hour power generation. The heat exchanger for converting thermal energy stored in solid particles to electricity enables the conversion of thermal energy into electrical energy for redistribution to the grid. In some embodiments, pressurized fluidized-bed heat exchangers may achieve efficient conversion of thermal energy to electricity by providing direct contact of the solid particles with a gas stream.

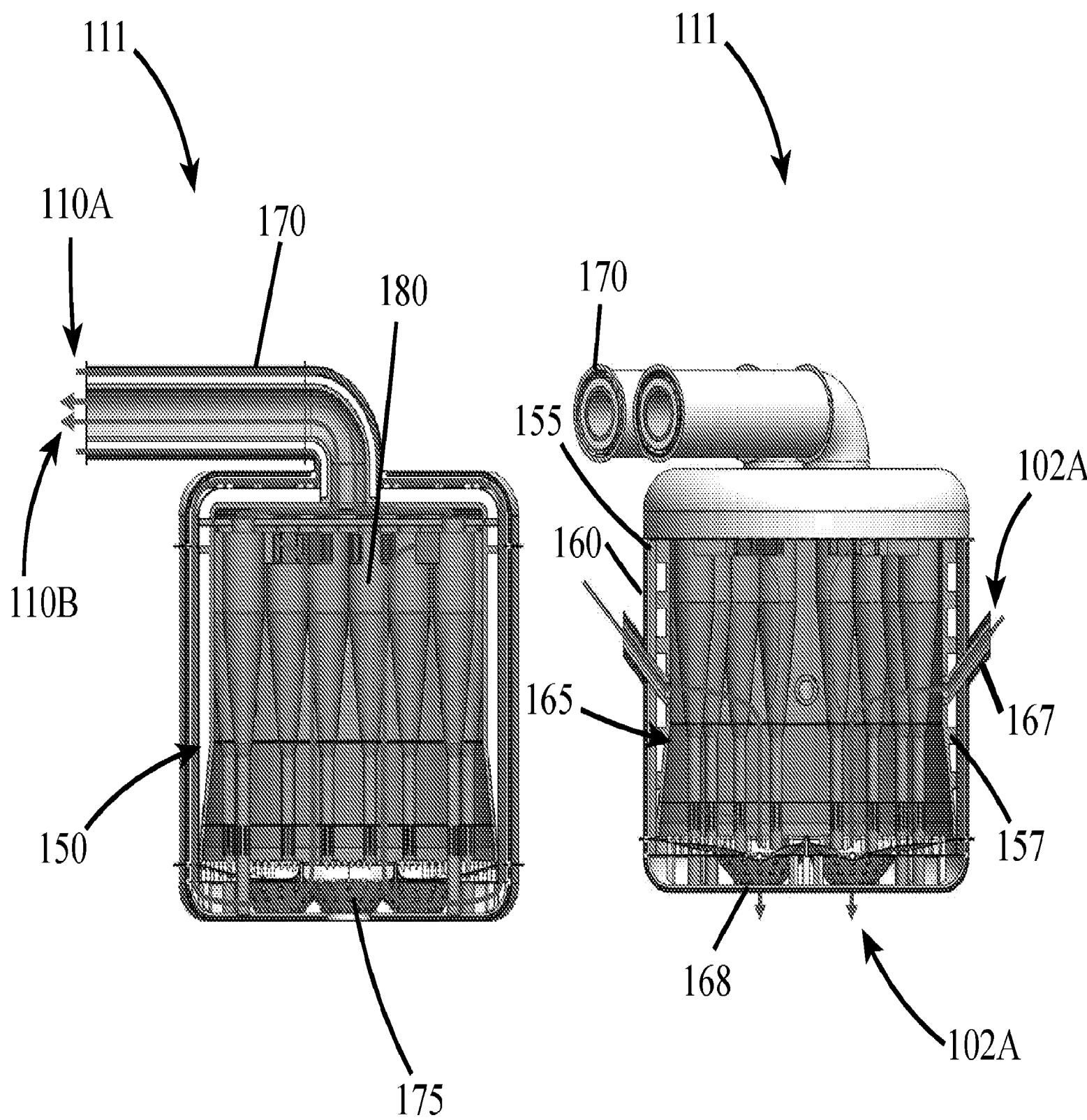


Figure 1C

FLUIDIZED-BED HEAT EXCHANGER FOR CONVERSION OF THERMAL ENERGY TO ELECTRICITY

CROSS-REFERENCE TO RELATED APPLIATIONS

5 This application claims the benefit of U.S. Provisional Application No. 63/052,128 filed on July 15, 2020, the contents of which are incorporated herein by reference in their entirety.

CONTRACTUAL ORIGIN

This invention was made with government support under Contract No. DE-AC36-08GO28308 awarded by the Department of Energy. The government has certain rights in the invention.

BACKGROUND

10 Renewable energy resources have been limited by the ability to store energy produced during off-peak times for use during peak times. Energy storage is important for variable-regeneration renewable energy sources, such as wind and solar. However, current battery technologies are too expensive for grid-scale, long duration energy storage. Molten salt storage is expensive and limited by salt stability and corrosion issues. Pumped energy storage in the form of hydroelectricity is limited by the
15 geological conditions of the system as it requires two reservoirs at different vertical levels. Thus, there remains a need for improved energy storage systems capable of storing excess electricity produced by alternative energy sources such as wind and solar, to be recovered later during peak electricity demand.

SUMMARY

20 An aspect of the present disclosure is a heat exchanger configured to transfer thermal energy between a gas stream and a stream of solid particles, the heat exchanger including a means for contacting the gas stream with the stream of solid particles resulting in a transfer of thermal energy between the gas stream and the stream of solid particles, in which the heat exchanger is configured to gravitationally pass the stream of solid particles through the means for contacting, and the heat exchanger is
25 configured such that the gas stream flows counter-current to the stream of solid particles. In some embodiments, the heat exchanger also includes an outer shell, and an inner shell, in which the means for contacting is positioned within the inner shell. In some embodiments, the heat exchanger also includes a gas inlet configured to direct the gas stream to the means for contacting. In some embodiments, the heat exchanger also includes a gas outlet configured to receive the gas stream from

the means for contacting. In some embodiments, the gas stream has a temperature, and the temperature is substantially greater at the gas outlet than at the gas inlet. In some embodiments, the gas stream has a temperature, the temperature is substantially lower at the gas outlet than at the gas inlet. In some embodiments, the gas inlet includes a first pipe, the gas outlet includes a second pipe, the second pipe is positioned concentrically within the first pipe creating a first annular space, and the gas stream is configured to flow through the first annular space. In some embodiments, the gas inlet includes a first pipe, the gas outlet includes a second pipe, the first pipe is positioned concentrically within the second pipe creating a first annular space, and the gas stream is configured to flow through the first annular space. In some embodiments, the inner shell is positioned within the outer shell creating a second annular space, and the gas stream is configured to flow from the first annular space to the second annular space. In some embodiments, the inner shell is positioned within the outer shell creating a second annular space, and the gas stream is configured to flow from the first annular space to the second annular space. In some embodiments, the means for contacting is an empty volume within the inner shell. In some embodiments, the heat exchanger includes a means for distributing the gas stream through the means for contacting, in which the means for distributing is positioned before the means for contacting, relative to the direction of flow of the gas stream through the heat exchanger. In some embodiments, the means for distributing comprises a plate having an orifice, and the orifice is connected to a bubble cap. In some embodiments, the means for distributing includes a plurality of pipes having at least one orifice. In some embodiments, the heat exchanger also includes a means for directing the solid particles stream to the means for contacting, in which the means for directing is positioned before the means for contacting, relative to the direction of flow of the stream of solid particles through the heat exchanger. In some embodiments, the heat exchanger includes an outer shell, and an inner shell, in which the means for directing includes a port which penetrates the inner shell and outer shell. In some embodiments, the means for contacting results in a portion of the stream of solid particles entrained within the gas stream. In some embodiments, the heat exchanger also includes a means for separating the stream of solid particles from the gas stream. In some embodiments, the means for separating comprises a nozzle having an inlet, a first outlet, and a second outlet, the inlet is configured to receive the gas stream and the stream of solid particles, the first outlet is configured to release the gas stream from the nozzle, and the second outlet is configured to release the gas stream from the nozzle. In some embodiments, the means for separating includes a filter. In some embodiments, the filter is a mesh filter.

An aspect of the present disclosure is a method for converting thermal energy to electrical energy, the method including transferring thermal energy from a plurality of solid particles to a gas stream using a heat exchanger, and using the gas stream to spin a turbine to generate electrical energy, in which the heat exchanger includes an outer shell, an inner shell positioned within the outer shell and having an internal volume, an annular space between the inner shell and the outer shell configured to allow the gas stream through the annular space, a pipe-in-pipe (PIP) gas line configured to direct the gas stream to the annular space, and a first port that penetrates the inner shell and the outer shell configured to direct the plurality of solid particles into the internal volume, in which the gas stream exits the annular space to pass through a distribution plate and into the internal volume, the internal volume is configured to contact the gas stream with the plurality of solid particles, the heat exchanger is configured such that the plurality of solid particles flow gravitationally through the internal volume to a second port located in the distribution plate configured to remove the plurality of solid particles from the heat exchanger, the heat exchanger is configured such that the gas flows counter-current to the plurality of solid particles to enter an upper portion of the internal volume, which is configured to separate the plurality of solid particles from the gas stream, and the PIP gas line is configured to remove the gas stream from the heat exchanger. The fluidizing gas velocity of the gas stream through the solids is optimized to maximize the heat transfer coefficient while minimizing the cross-sectional plan area, and therefore, the size of the inner annular space.

BRIEF DESCRIPTION OF THE DRAWINGS

Some embodiments of the present disclosure are illustrated in the referenced figures of the drawings. It is intended that the embodiments and figures disclosed herein are to be considered illustrative rather than limiting.

Figure 1A illustrates a thermal energy storage system, including a pressurized fluidized-bed heat exchanger (PFB HX), according to some embodiments of the present disclosure.

Figure 1B illustrates a process flow diagram of a PFB HX, according to some embodiments of the present disclosure.

Figure 1C illustrates generalized flow paths of gas (left) and solid particles (right) through an exemplary PFB HX, according to some embodiments of the present disclosure.

Figure 2 illustrates an exemplary PFB HX, according to some embodiments of the present disclosure.

Figure 3 illustrates a flow diagram of how gas and particles move through the thermal energy storage system of Figure 1A, according to some embodiments of the present disclosure.

5 Figure 4 illustrates the geometry used in a finite element analysis (FEA) of insulating designs, according to some embodiments of the present disclosure. Refractory is the dark brown, the voids were filled with calcium silicate fiber, and there is a thin, steel shell. Panel (b) illustrates the thermal boundary conditions applied to the FEA problem. Adiabatic conditions were applied to the top and bottom boundaries.

10 Figure 5 illustrates the relationship between the outside diameter of the fluidized-bed, as defined by the inner shell, when insulation is included and the velocity (circles, left axis) and Reynolds number (squares, right axis) of the air that flows around the PFB, according to some embodiments of the present disclosure.

Figure 6 illustrates a steady-state temperature distributions from the FEA analysis of the interior, 15 Panel (a), and the exterior faces, Panel (b), of an exemplary insulation design selected for an exemplary PFB HX, according to some embodiments of the present disclosure. All units are in Celsius. Black lines in (a) mark changes in materials.

Figure 7 illustrates a pressure vessel shell design for a PFB HX, for the outer shell, using mineral wool insulation with a steel shell, according to some embodiments of the present disclosure.

20 Figure 8 illustrates that the gas velocity as a function of its vertical position within a fluidized-bed stays in a range of smooth fluidization, according to some embodiments of the present disclosure.

Figure 9 illustrates a first exemplary gas distributor (left), according to some embodiments of the present disclosure. An individual “bubble-cap” is illustrated on the right. The solid line illustrates gas flow through the bubble cap.

25 Figure 10 illustrates a second exemplary gas distributor, according to some aspects of the present disclosure.

Figure 11 illustrates a nozzle (i.e., cyclone) design for gas/solid particle separating, according to some embodiments of the present disclosure. The cross-sectional view of the PFB HX, highlighting the position of the 16 cyclones is shown on the left. The general flow of the solid particles and gas within the nozzle is shown in the center and the dimensions used for this exemplary nozzle design is shown on the right.

Figure 12 illustrates a schematic of a particle feeding system to a PFB HX, utilizing a lock hopper, according to some embodiments of the present disclosure.

Figure 13 illustrates a schematic of the pipe-in-pipe gas-line design, according to some embodiments of the present disclosure.

10

REFERENCE NUMERALS

	100.....energy storage system
	101.....silo
	102.....solid particles and/or solid particle stream
	103.....turbine
15	104.....generator or motor
	105.....substation
	106.....grid line
	107.....particle conveyor
	108.....particle heater
20	109.....electrical supply line
	110.....gas and/or gas stream
	111.....pressurized fluidized-bed heat exchanger (PFB HX)
	112.....shaft
	120.....means for contacting
25	130.....means for distributing
	140.....means for directing
	150.....fluidized-bed
	155.....inner shell
	157.....second annular space
30	160.....outer shell

	165.....	inner volume
	167.....	first port
	168.....	second port
	170.....	pipe-in-pipe gas line
5	175.....	gas distributor
	177.....	upper portion
	180.....	nozzle
	185.....	bubble cap
	186.....	head pipe
10	187.....	manifold pipe
	190.....	lock hopper
	195.....	skip hoist

DETAILED DESCRIPTION

The present disclosure may address one or more of the problems and deficiencies of the prior art discussed above. However, it is contemplated that some embodiments as disclosed herein may prove useful in addressing other problems and deficiencies in a number of technical areas. Therefore, the embodiments described herein should not necessarily be construed as limited to addressing any of the particular problems or deficiencies discussed herein.

References in the specification to “one embodiment”, “an embodiment”, “an example embodiment”, “some embodiments”, etc., indicate that the embodiment described may include a particular feature, structure, or characteristic, but every embodiment may not necessarily include the particular feature, structure, or characteristic. Moreover, such phrases are not necessarily referring to the same embodiment. Further, when a particular feature, structure, or characteristic is described in connection with an embodiment, it is submitted that it is within the knowledge of one skilled in the art to affect such feature, structure, or characteristic in connection with other embodiments whether or not explicitly described.

As used herein the term “substantially” is used to indicate that exact values are not necessarily attainable. By way of example, one of ordinary skill in the art will understand that in some chemical reactions 100% conversion of a reactant is possible, yet unlikely. Most of a reactant may be converted to a product and conversion of the reactant may asymptotically approach 100%

conversion. So, although from a practical perspective 100% of the reactant is converted, from a technical perspective, a small and sometimes difficult to define amount remains. For this example of a chemical reactant, that amount may be relatively easily defined by the detection limits of the instrument used to test for it. However, in many cases, this amount may not be easily defined, hence the use of the term “substantially”. In some embodiments of the present invention, the term “substantially” is defined as approaching a specific numeric value or target to within 20%, 15%, 10%, 5%, or within 1% of the value or target. In further embodiments of the present invention, the term “substantially” is defined as approaching a specific numeric value or target to within 1%, 0.9%, 0.8%, 0.7%, 0.6%, 0.5%, 0.4%, 0.3%, 0.2%, or 0.1% of the value or target.

As used herein, the term “about” is used to indicate that exact values are not necessarily attainable. Therefore, the term “about” is used to indicate this uncertainty limit. In some embodiments of the present invention, the term “about” is used to indicate an uncertainty limit of less than or equal to $\pm 20\%$, $\pm 15\%$, $\pm 10\%$, $\pm 5\%$, or $\pm 1\%$ of a specific numeric value or target. In some embodiments of the present invention, the term “about” is used to indicate an uncertainty limit of less than or equal to $\pm 1\%$, $\pm 0.9\%$, $\pm 0.8\%$, $\pm 0.7\%$, $\pm 0.6\%$, $\pm 0.5\%$, $\pm 0.4\%$, $\pm 0.3\%$, $\pm 0.2\%$, or $\pm 0.1\%$ of a specific numeric value or target.

Among other things, the present disclosure relates to heat exchangers for converting thermal energy stored in solid particles to electricity. Electro-thermal energy storage directly converts off-peak electricity into heat for thermal energy storage, which may be converted back to electricity, for example during peak-hour power generation. Thus, electro-thermal energy storage will, among other things, enable better incorporation of intermittent renewable energy sources such as solar and wind into existing electrical grids, which will in turn result in improved grid resilience. The heat exchanger for converting thermal energy stored in solid particles to electricity is an important part of an electro-thermal energy storage system, as it enables the conversion of thermal energy into electrical energy for redistribution to the grid. Thus, among other things, the present disclosure describes heat exchangers for this important energy conversion step. In some embodiments of the present disclosure, pressurized fluidized-bed heat exchangers (PFB HX) may achieve efficient conversion of thermal energy to electricity by providing direct contact of the solid particles with a gas stream. In some embodiments of the present disclosure, a fluidized-bed heat exchanger may utilize a multilayer configuration where the relatively hot gas resulting from the contacting of a relatively cold gas with the hot solid particles is then used to drive turbomachinery to generate

electricity. As described herein, in some embodiments of the present disclosure, a fluidized-bed heat exchanger may use direct gas/particle contact to eliminate heat transfer surfaces, thus eliminating or reducing at least some of the ultrahigh temperature operations needed in an electro-thermal energy storage system.

5 Figure 1A illustrates an energy storage system 100, according to some embodiments of the present disclosure. In this exemplary energy storage system 100, a silo 101 (i.e., a storage vessel; four shown 101A-D) is provided, which may be utilized for the storage of solid particles 102. A particle heater 108, as described in detail herein, may be positioned near and/or inside the silo 101, such that the particle heater 108 is configured to heat the solid particles 102 from a first relatively low
10 temperature (e.g., between about 250 °C and about 500 °C) to a second relatively high temperature (e.g., between about 850 °C and about 1200 °C) during a “charging mode”, where the solid particles are heated using electricity. Thus, a particle heater 108 may be an electric heater (e.g., using resistive heating elements), with the electric power needed to drive the particle heater 108 provided from the grid as shown by electrical supply line 109 shown in Figure 1A. The heated
15 particles 102, and the thermal energy stored within the solid particles 102, may then be stored within a silo 101 until such a time when the local or regional electrical needs (e.g., time periods of peak capacity) require that the thermal energy stored in the heated particles be converted back to electricity.

In some embodiments of the present disclosure, the thermal energy stored in the solid particles 102
20 may be converted to electricity by passing the hot solid particles 102 through a heat exchanger that transfers heat from the particles 102 to a heat transfer fluid or working fluid (i.e., gas and/or gas stream 110). For example, the hot solid particles 102 may be transported from the silo 102 to a fluidized-bed heat exchanger 111 in which the hot solid particles 102 come into direct contact with the gas 110. As shown in Figure 1A, in some embodiments of the present disclosure, a fluidized-
25 bed heat exchanger 111 may be integrated into a silo 102, such that the hot solid particles 102 may be transported by gravity from within the silo 102 to the fluidized-bed heat exchanger 111. In some embodiments of the present disclosure, for example when the fluidized-bed heat exchanger 111 is not integrated into the silo 102, the hot solid particles 102 may be transported to a fluidized-bed heat exchanger 111 gravitationally, pneumatically, non-mechanically (e.g., L-valves, J-valves,
30 loop seals, etc.), and/or mechanically (e.g., by the use of a conveyer similar to particle conveyor 107). As shown in Figure 1A, a fluidized-bed heat exchanger 111 may be configured to transfer

heat from the solid particles 101 to a gas 110, (e.g., a heat transfer fluid or working fluid), thereby heating the gas 110 to a temperature between about 700 °C and about 1200 °C and cooling the solid particles 102 to a temperature between about 250 °C and about 500 °C. The heated gas 110 may be subsequently directed to a turbine 103, which in turn may drive a shaft 112 connected to a generator or motor 104, such that the thermal energy recovered from the solid particles 102 is converted to electrical energy 109, which may then be transferred to a substation 105 and finally to a grid line 106 for transport to the power grid. The now expanded and cooled gas 110 may then be directed to a compressor (not shown) to provide the driving force needed to circulate the gas 110 back through the fluidized-bed heat exchanger 111.

Figure 1B illustrates a process flow diagram of a pressurized fluidized-bed heat exchanger (PFB HX) 111, according to some aspects of the present disclosure. In the example shown in Figure 1B, the PFB HX 111 includes a stream of solid particles 102 and a gas stream 110. The two meet for the exchange of thermal energy in a means for contacting 120 the solid particles 102 and the gas 110. In some embodiments, prior to entering the means for contacting 120, the gas 110 may go through a means for distributing 130 the gas 110. In some embodiments, prior to entering the means for contacting 120, the solid particles 102 may go through a means for directing 140 the solid particles 102.

Figure 1C illustrates a PFB HX 111, according to some embodiments of the present disclosure. The left panel highlights the flow of gas 110 through the PFB HX 111. The right panel highlights the flow of solid particles 102 through the PFB HX 111. A relatively cold gas 110 (e.g., about 300 °C) from a compressor (not shown in Figure 1A) directs the gas 110A to a pipe-in-pipe (PIP) gas-line 170 constructed of an inner pipe concentrically positioned within an outer pipe, thus creating an annular space through which the incoming cool gas 110A flows. The PIP gas-line 170 directs the cool gas to an inner volume 165 (i.e., an annular space) formed by an inner shell 155, which contains the fluidized-bed 150 portion of the PFB HX 111, and an outer shell 160. While flowing through the inner volume 165, the gas 110 helps keep both shells (i.e., inner shell 155 and outer shell 160) relatively cool, allowing less expensive materials of construction to be used.

Eventually the gas 140 reaches the bottom of the PFB HX 111 to enter the fluidized-bed 150 where one or more gas distributors 175 evenly distribute the gas 110 across the cross-sectional area of the fluidized-bed 150. This in turn provides a uniform and consistent gas-to-solid ratio as a function of position within the fluidized-bed and maximizes heat transfer and efficiency. The gas 110 flows in an upward direction through the fluidized-bed 150, contacting the downward flowing solid particles 102. The solid particles 102A enter the PFB HX 111 through ports (i.e., first port 167) penetrating the outer shell 160 and the inner shell 155 to enter the fluidized-bed 150. The solid particles 102 fall by gravity to eventually collect on the gas distributors 175, where contact with the up-flowing gas 110 is promoted. During their fall through the fluidized-bed 150, the initially hot solid particles 102 are cooled to a temperature approaching that of the incoming gas 110A (e.g., about 300 °C). The cooled particles 102A then exit the PFB HX 111 through one or more lock-hoppers (190 shown in Figure 13).

Simultaneously, the relatively cool up-flowing gas 110 contacts the relatively hot down-flowing solid particles 102 within the fluidized-bed 150 whose inner volume 165 is defined by the inner shell 155, resulting in a hot gas 110B exit exiting at a temperature that approaches that of the incoming solid particles (e.g., about 1200 °C). Internal baffles (not shown) may be positioned within the fluidized-bed 150 to divide it into separate sections, which can minimize backflow of both the gas 110 and the solid particles 102, thus improving performance of the PFB HX 111. In some embodiments, the fluidizing gas superficial velocity may be optimized to promote good lateral mixing of the downward flowing particles across the plan area of the inner volume, which may improve the performance of the PFB HX 111. The upper-most volume within the inner shell 155 is utilized for separating the solid particles 102 from the gas 110. An impingement plate (not shown) may prevent direct entrainment of solid particles 102 with the gas 110. One or more cyclones 180 provide most of the solid particle removal, resulting in a clean and hot gas stream 110B that exits the PFB HX 111, through the PIP gas line 170, to be directed to the electricity generating turbine (103), thereby accomplishing the objective of converting the solid particles 102 stored thermal energy into electrical energy.

Figure 2 illustrates an exemplary design concept for a PFB HX 111 for the transfer of thermal energy from solid particles 102 to gas 110 to be used to drive a turbine 103 to generate electricity, according to some embodiments of the present disclosure. In some examples, such a PFB HX 111 may be adapted and/or modified to achieve a low-profile arrangement of the PFB HX 111 relative to the hot-particle silos 101 storing solid particles 102 at about 1,170 °C. As described herein, a PFB HX 111 may include an external, outer shell 160 that houses an inner shell 155, creating a gas gap between the inner shell 155 and the outer shell 160. The gas 110, which is a water/air mixture and may be supplied by the Brayton combined-cycle power (BCCP) compressors, may be directed to the PFB HX 111 to enter the gap between the inner shell 155 and the outer shell 160, thereby maintaining the exterior wall temperatures of the outer shell 160 at temperatures low enough (e.g., less than 350 °C) to allow the use of low-cost steels. Supply lines may then direct the gas 110 to one or more distributors, which evenly distribute the gas 110 across the PFB HX's 111 cross-sectional area dedicated to direct solid particles/gas contact. Thus, the gas flows through the PFB HX, contacting the particles, such that they are eventually heated to the desired exit temperature (e.g., greater than 1,170 °C).

Simultaneously, the solid particles are cooled as they are fluidized and eventually fall through the PFB HX 111 to eventually exit at their desired exit temperature (e.g., about 300 °C). The cooled solid particles 102 and the heated gas 110 are then directed to at least one nozzle 180 (i.e., a cyclone) (or two or more configured in parallel) to achieve solid particle/gas separation, by directing the solid particles 102 through the nozzle 180, with the gas 110 exiting the top of the nozzle 180 as hot, clean (i.e., without solid particles 102) gas 110 that can be subsequently directed to the turbine 103. Among other things, PFB HX 111 operating conditions described herein are designed for integration into the thermal energy storage (TES) system 100. Aspects of such integration include properly connecting the PFB HX 100 with the TES system 100 for charging and discharging solid particles 102, optimizing pressurized fluidization conditions, designing a steam (or superficial carbon dioxide) heat exchanger, and gas 110 clean-up. The exemplary PFB HX 111 design shown in Figure 2 was developed has numerous unique innovations. First, this concept is suitable for the fluidization of inert solid particles 102 to heat a pressurized gas 110. Further, the design an outer pressure vessel (i.e., outer shell 160) in which occurs the direct contact of solid particles 102 with gas 110, thereby encapsulating all of the heat transfer in a compact unit. The PFB HX 111 designs described herein also consider the capacity required for long-term energy

storage requiring multiple particle storage silos 101, which may be arranged around a single PFB HX 111, with each silo 101 feeding the PFB HX 111 through dedicated pipe or conduit to individual inlets positioned in the sides of the PFB HX 111; e.g., four particle inlets (i.e., ports 167) for four silos 101 were utilized in this design, although this should not be limiting is provided for illustrative purposes. Further, a solid particle 102 exit port 168 may be designed to provide even distribution of solid particles 102 within the PFB HX 111, as well as uniform heating of the gas 110.

Figure 3 illustrates a flow diagram of how a solid particle stream 102 and a gas stream 110 flow through the parts of a PFB HX 111, according to some embodiments of the present disclosure.

Thermal energy stored in hot solid particles 102 heat a compressed gas 110 that drives a power turbine 103 for electricity production. The PFB HXs 111 described herein are designed to maximize the gas-solid particle heat transfer while maintaining an acceptable pressure drop through the heat exchanger 111. Among other things, the PFB HX 111 designs described herein provide a countercurrent gas 110/solid particle 102 flow to heat the gas 110 to a temperature close to that of the incoming hot solid particles 102 while cooling the solid particles 102 to a temperature approaching that of the incoming gas 110.

To achieve the objective of simultaneously heat the gas 110 while cooling the solid particles 102, numerous engineering innovations were needed including process control, bed layout, particle flow, particle handling, and process integration. In some embodiments of the present disclosure, the PFB HX 111 may connect directly with a compressor and/or a turbine 103. In some embodiments of the present disclosure, a PFB HX 111 may have an outer shell 160 that maintains the gas 110 pressure and an inner shell 155 that contains a high-temperature core for heat transfer between the gas 110 and the solid particles 102. The walls of an inner shell 155 may be insulated using at least one of a refractory layer and/or ceramic fiber insulation. The flow paths of both the solid particles 102 and the gas 110 through a PFB HX 111 and a larger energy storage system 100, as described herein, are illustrated in Figure 3.

Although solid particle 102 weight may be sufficient to achieve gravitational flow of the solid particles 102 into a PFB HX 111, the weight may not be adequate to overcome the pressures and flow resistances present in a PFB HX 111. Thus, in some embodiments of the present disclosure, solid particles 102 may feed through a high-temperature lock hopper (190 shown in Figure 13)

connected to a storage silo 101. The lock hopper 190 may then feed the PFB HX 111 by charging the lock hopper 190 in an unpressurized state by gravitationally feeding the solid particles 102 into the lock hopper, then pressurizing the lock hopper 190 to the pressure (or greater than) the inlet pressure of the PFB HX 111, followed by discharging the solid particles 102 into the PFB HX 111.

- 5 In some embodiments of the present disclosure, a mixture of compressed air and steam from a power island may be directed into a PFB HX 111. In some embodiments of the present disclosure, the low-temperature mixture of air and water fed into the outer shell 160 of the PFB HX 111 may provide significant cooling capacity to cool the outer shell 160 to temperatures compatible with carbon steel as the material of construction for the outer shell 160.
- 10 In some embodiments of the present disclosure, the fluidization velocity to fluidize the solid particles 102 may be above a minimum fluidization velocity, but below the turbulent regime and particle terminal velocity. The multi-layer fluidized-bed 150 may use a refractory grid material (i.e., mesh or a filter) to prevent solid particle 102 mixing along the top of the bed to accomplish countercurrent gas 110/solid particle 102 flow and to maintain the desired temperature gradient.
- 15 The PFB HX 111 is designed to achieve direct contact and countercurrent flow between the solid particles 102 and the gas 110, while providing adequate height to enable the solid particles 102 to disengage from the gas 110. In some embodiments of the present disclosure, an impingement device may be implemented to enhance separation of the solid particles 102 from the gas 110 in order to successfully return the solid particles 102 back to the PFB HX 111. As shown herein, the
- 20 hot gas 110 and the cool solid particles 102 may be separated using one or more nozzles 180 (i.e., cyclones) positioned inside the inner shell 155 forming the pressure vessel. In some embodiments of the present disclosure, the cool solid particles 102 may exit the PFB HX 111 through a low-temperature rotary valve positioned at the bottom of the PFB HX 111 to be collected by a conveyor 107, which then transports them (e.g., by a skip hoist 195 shown in Figure 13) to a storage silo
- 25 101.

Gas-particle heat transfer is an important step in both the energy storage charging (i.e., electricity to thermal energy conversion) and energy discharging (i.e., thermal energy to electricity conversion) processes. In some embodiments of the present disclosure, for energy discharging, a PFB HX 111 may be configured to provide direct heat transfer between the hot solid particles 102

30 and a pressurized gas 110 to heat the gas 110 to drive a turbine 103. Such direct gas/solid particle

contact reduces or eliminates the cost and exergy losses resulting from heat exchanger surfaces commonly found in indirect heat exchangers. In the energy storage system described herein, the hot gas 110 exits the PFB HX 111 at temperatures sufficiently high to drive a high-efficiency Brayton combined-cycle power (BCCP) system. Aspects of the PFB HX 111 and BCCP
5 integration described herein may be based on a gas-turbine combined cycle (GTCC) system and/or a commercial pressurized fluidized-bed combustion plant integrated with a GTCC system.

Among other things, the PFB HX 111 designs described herein enable operational temperatures of at least 1,200 °C, which further enables its integration with a BCCP system. PFB HX 111 innovations disclosed herein include fluidizing inert solid particles 102 at temperatures at least 300
10 °C higher than those common in commercial pressurized fluidized-bed plants, while achieving low pressure drops, high heat-transfer rates, effective gas/particle separation, and enabling the integration with the thermal energy storage (TES) and/or the BCCP system. The PFB HX 111 technology described herein is, among other things, more efficient, compact, and provides higher particle heat-transfer coefficients than what can typically be achieved for heating gas 110 in a
15 traditional heat exchanger, where the solid particle/gas heat transfer occurs through a heat transfer surface. Some performance parameters for the PFB HX 111 designs described herein include the heated and pressurized gas 110 achieving exit temperatures greater than 1,170°C (to meet the BCCP thermal load), and, in some embodiments, gas 110 pressure drop through the PFB HX 111 of less than 5% of the inlet pressure. As described below, fluidization conditions and gas/solid
20 particle separation metrics occurring inside the PFB HX 111 were analyzed to provide design and operational insights and guidance for future full-scale PFB HX 111 designs. For example, the fluidizing velocity of the gas stream 110 (i.e., superficial gas velocity) may be optimized to maximize the heat transfer coefficient at mildly fluidized conditions while providing a cost effective cross-sectional area plan of the PFB HX 111 to minimize the internal volume of the PFB
25 HX 111 and thus cost. Further, a mildly fluidized-bed 150 condition provides the possibility for a more pronounced top-to-bottom temperature gradient with the highest temperature solid particles 102 at the top surface of the fluidized bed 150, which may heat the counter flowing gas stream 110 to a higher temperature than a typical well-mixed, well-fluidized bed with its typical top-to-bottom temperature gradient. In the PFB HX 111, there may be a net downward (i.e., gravitational) flow
30 of solid particles 102 counter-current to the upward (i.e., opposite of gravity) flowing gas stream 110.

In some embodiments of the present disclosure, a PFB HX 111 may be integrated with a power generation system by utilizing, among other things, a pipe-in-pipe (PIP) 170 gas line. A compressor in the power generation system may supply a pressurized, low-temperature gas through to the annular space created by the PIP 170 configuration to be subsequently directed into the PFB HX 111. The low-temperature gas may flow through the annular space of PIP 170 gas line, and subsequently through an inner space (i.e., a jacket) created by positioning the outer shell 160 of the PFB HX 111 around an inner shell 155. As described above, low-temperature inlet gas 110 provides cooling capacity to the outer shell 160 to provide sufficiently low operating temperatures for the outer shell 160, while also cooling the material making up the inner shell 155.

The now somewhat preheated compressed gas 110 may enter the fluidized-bed 150 portion of the PFB HX 111 contained within the inner shell 155, by being directed to gas distributor 175 positioned at the bottom of the PFB HX 111, where it contacts and fluidizes the downward flowing solid particles 102 in a counter-current and direct contact mode, thereby heating the gas 110 and cooling the solid particles 102. The heated gas 110 may then exit from the top of the PFB HX 111 after being separated from the solid particles 102 in a gas-solid separations unit operation, such as one or more nozzles 180. This removal of the clean hot gas 110 may be achieved by directing it once again through the PIP 170 gas line, but this time through the central pipe of the PIP 170 gas line, where it is subsequently directed to turbine 103 that converts the energy transferred from the solid particles 102 to the gas 110 to electrical energy.

As described herein, the fluidized-bed 150 positioned within the inner shell 155 contains the hot solid particles 102 and operates at high temperatures. Thus, the walls of the inner shell 155 may be insulated using refractory and/or other materials, e.g., at least one of the outer surfaces and/or inner surface of the metal inner shell 155. As describe above, an inner shell 155 constructed of metal may be in contact with the low-temperature inlet compressed gas 110. The combination of cooling provided by the low-temperature gas 110 entering and flowing through the jacket, with insulating the inner shell 155 helps maintain a low outer shell 160 operating temperature. This design may also result in a relatively small pressure drops occurring in the PFB HX 111, because the fluidized-bed 150 is contained within the pressurized inner shell 155.

To minimize or prevent the high-temperature core from losing heat to the cooler outer shell 160, insulation may be positioned on the inside wall of the inner shell 155; the space formed by the inner shell and the outer shell may be described as follow: outer shell insulation – outer shell metal – jacket space for incoming air – inner shell metal – inner shell insulation. Using finite element analysis (FEA) software, an insulation design for the inner shell that meets the constraints of the PFB HX temperature profiles and operating conditions was determined. The model description can be found in Figure 4. Figure 4 illustrates the geometry used in the steady-state FEA analysis. The geometry corresponded to a 14.0-m diameter inlet, contracting to 13.0-m diameter through a 4.0 m dense phase region (i.e., fluidized-bed 150), and a 6.0 m tall freeboard section; The design is based on the operating condition of a 270 MWt PFB HX 111 integrated into an electro-thermal energy storage system 100, as illustrated in Figure 1A.

The insulation layer of the inner shell 155 may include thick refractory rods that may protrude from the refractory shell to attach to the steel inner shell 155 for structural support. The cavities within the refractory structures may be filled with, for example, calcium silicate (Ca_2SiO_4 or CalSil) insulation fibers (see Figure 1B). Calcium silicate has superior insulating properties, is lightweight, and cheaper than refractory materials, but lacks the strength of refractory structures. The dense phase region (i.e., fluidized-bed 150) has a linear temperature profile rising from 300 °C near the inlet/bottom to 1200 °C at the top of the fluidized-bed 150 representing the temperature gradient expected in the dense phase portion of the PFB HX 111 as the solid particles 102 cool as they fall, and the gas 110 heat up as it rises. The freeboard region was characterized by convection between the wall and the heated gas 110. The exterior of the metal shell boundary condition was also convective with an ambient air temperature of 300 °C (the gas return temperature from turbine and compressor) and heat transfer coefficients were estimated by correlations for annular pipes. The corresponding correlations are summarized in Eq. (1) and (2) below.

$$Nu = \frac{hL}{k} = 0.022Re^{0.8}Pr^{0.6} \quad (1)$$

$$Nu = \frac{hL}{k} = \frac{\left(\frac{\xi}{8}\right) Re Pr}{K_1(\xi) + K_2(\xi) \left(Pr^{\frac{2}{3}} - 1\right) \left(\frac{\xi}{8}\right)^{\frac{1}{2}}} \quad (2)$$

Where:

$$\xi = (1.82 \log(Re) - 1.64)^{-2}$$

$$K_1(\xi) = 1 + 3.4\xi \quad K_2(Pr) = 11.7 + 1.8Pr^{-1/3}$$

The properties of air at 300 °C were used to approximate the properties of the gas 110 and were held constant for all cases; these values are summarized in Table 1 below.

Table 1. Material and material properties used in the insulation design study.

Property	Symbol	Value	Units
Density	ρ	0.6172	kg/m ³
Thermal conductivity	k	0.0450	W/m-K
Heat capacity	c_p	1045.00	J/kg-K
Prandtl number	Pr	0.6800	-

- 5 The Reynolds number, Re , changed based on the outer diameter of the metal shell, as the outer diameter of the metal shell for the inner bed approached the inner diameter of the pressure vessel (15.0 m) the velocity, v [m/s], increased to maintain a constant mass flow rate of air for all cases. The relationship between outside diameter of the inner bed and the air velocity and Reynolds number is shown by Figure 5. This fully defines the thermal boundary conditions used in the
- 10 insulation model. **Error! Reference source not found.** lists the materials and their associated properties that are input parameters in the FEA study.

Table 2. Material and material properties used in the insulation design study.

Material	Density [kg/m ³]	Heat Capacity [J/kg-K]	Thermal Conductivity [W/m-K]	Source
Petromax® 700 LTM	1000.0	1000.0	0.30	Allied
CalSil Fiber (1400 °C)	64.0	1000.0	0.11	JR Refractory
Structural Steel	7850.0	434.0	60.50	ANSYS Mechanical

Panels (a) and (b) of Figure 6 illustrated the selected insulation design and the resultant temperature distribution. This is for illustrative purposes and is not intended to be limiting. For this exemplary insulation design, the outside diameter of the inner shell 155, D , was set to 14.40 m. The refractory was 200 mm thick excluding the supporting rods. The CalSil fiber was 475 mm thick at the thickest point (the freeboard region). The metal wall of the inner shell 155 was 25 mm thick.

In Panel (a) of Figure 6, the applied linear temperature profile in the dense phase region (i.e., the fluidized-bed 150) can be seen. The convective boundary condition applied to the interior surface in the freeboard region resulted in the wall temperature being very close to 1200 °C. Panel (b) of Figure 6 illustrates the exterior wall temperature distribution. Small hot spots are visible where the refractory support rods come in contact with the metal of the inner shell 155; this is expected as the refractory has a thermal conductivity three times higher than that of the CalSil fiber. For this exemplary case, the exterior temperatures of hot spots were 304.14 °C and 304.32 °C using the Kays and Petukhov Popov correlation, respectively. Using the average of the two average exterior temperatures, the gas 110 temperature rise from flowing around the high-temperature core was predicted using Eq. (3) below.

$$\ln \left(\frac{T_{ext} - T(x)}{T_{ext} - T_{in}} \right) = \frac{-4hDx}{\rho c_p v (15^2 - D^2)} = -Cx$$

$$T_{out} = T(x = L) = T_{ext} - (T_{ext} - T_{in})e^{-CL} \quad (3)$$

The calculation showed the gas 110 was only predicted to rise about 2.3 °C, a relatively insignificant temperature rise. Therefore, the insulation design was validated as being sufficient to meet the design constraints of an exemplary PFB HX 111 design.

The outer shell 160 holds the pressure of the fluidized-bed 150 and, therefore, must be designed to withstand the pressure differential between the interior and exterior pressures, which in some embodiments of the present disclosure, may be about 20 bar. If the hot-temperature core was not well insulated and/or if the cool inlet gas 110 was not directed between the inner shell 155 and the outer shell 160, more expensive, high-temperature steel and/or alloys would be required. However, since the PFB HX 111 may include design features, the outer shell 160 may operate at relatively low temperatures. The outer shell 160 may also be insulated to prevent heat loss to the ambient air. Figure 7 illustrates an exemplary structure of an outer shell 160, according to some aspects of

the present disclosure. The associated dimensions for the insulation found using a one-dimensional (1D) heat resistance model are AISI 4340 Steel (1) 0.100 m, mineral wool (2) 0.150 m, and A36 steel shell (3) of 0.0127 m.

The design for a PFB HX 111 may be highly dependent on the operating conditions of the TES system 100. Additionally, compared to other parts of the power system, the PFB HX 111 significantly affects the TES system 100 design. The basic size for a PFB HX 111 vessel, the gas pressure drops, as well as the heat losses to the ambient environment were calculated to explore system design requirements, which are summarize in Table 3 for an exemplary PFB HX 111.

Table 3. Preliminary PFB design dimensions and key parameters.

Specification	Unit	Value
PFB Pressure Vessel ID	m	15.00
PFB Pressure Vessel OD	m	15.52
PFB Pressure Vessel Height	m	15.18
PFBHX Height	m	13.30
PFBHX Dense Region ID	m	14.00
PFB Freeboard Region ID	m	13.00
PFBHX Minimum Fluidization Velocity	m/s	0.166
Calculated Required Cyclone Number	-	15 (16 used)
Cyclone Inner Diameter	m	2.25
Calculated Cyclone Efficiency	%	99.934

The minimum fluidization velocity changes with the operating temperature and pressure inside the PFB HX 111. For the exemplary design described herein, the fluidized-bed 150 portion of the PFB HX 111 was designed based on three times (3X) the minimum fluidization velocity and thus fluidization will rise with an increase in temperature along the bed height. In some embodiments of the present disclosure, in order to minimize the fluidization mixing and backflow of solid particles 102 and/or gas 110, which can reduce the temperature gradient between the solid particles 102 and gas 110, the fluidized-bed 150 portion of a PFB HX 111 may be separated in the vertical direction into sections divided by baffles. Figure 8 illustrates the gas 110 velocity as a function of fluidized-bed height, resulting from temperature changes. The selected fluidization velocity was below the velocity of a turbulent bed and the particle terminal velocity, to minimize solid particle 102 entrainment in the gas exiting the top of the fluidized bed 150. In some embodiments, the heat transfer coefficient may be optimized in the range of two to three times the minimum fluidization

velocity. The bed height accommodates a gas/solid particle disengagement distance as a first stage of gas/particle separation. Baffles may be utilized to minimize particle entrainment, with any remaining solid particles 102 in the gas 110 being removed by a nozzle 180 (i.e., cyclone separator) before the heated gas 110 is returned to the turbine 103 for electricity generation.

5 Means for distributing 130 (i.e., gas distributors 175) may play an important role in fluidization quality and pressure drop. Examples of typical of gas distributors include perforated or porous plate, bubble caps and nozzles, spargers (laterally or downwardly flow), conical grid, and pierced sheet grids. Perforated plate distributors were selected for the analysis described herein, although other distributor types could have been selected. Figure 9 illustrates a gas distributor having
10 nozzles with bubble caps. A perforated plate is simple and may be easily implemented. Perforated plates may be used as baffles to form a multilayer (i.e., multizone) fluidized-bed 150 in the PFB HX 111 as described above. In some embodiments of the present disclosure, a bubble caps (185 as shown in Figure 9) of a gas distributor 175 and/or baffle may penetrate into a layer of solid particles 102 that have collected on the gas distributor 175/baffle, thereby directing the gas 110
15 directly into the layer of solid particles 102 to promote mixing, fluidization, and/or heat transfer. As shown in Figure 10, bubble caps 185 may be implemented to cover the tops of the nozzles (referred to herein as a “bubble-cap nozzle”) to prevent solid particles 102 from clogging the nozzles. In some embodiments of the present disclosure, a baffle plate may be used as a gas distributor 175 where gas 110 moves up and solid particles 102 fall downward through it (i.e., the
20 solid particles 102 fall through the port 168).

Referring again to Figure 9, the exemplary gas distributor 175 evaluated in this example included 400 individual nozzles (i.e., bubble caps 185). The nozzles were distributed across the 14.0-m diameter floor of the inner shell, e.g., the fluidized-bed 150 portion of the PFB HX 111. In this example, the nozzles were positioned below a perforated plate to smooth gas 110 flow, among
25 other things. This exemplary gas distributor 175 included four cones (i.e., ports 168) to collect the solid particles 102 that had passed through fluidized-bed 150, in order to funnel them out of the PFB HX 111 through four lock hoppers (190 shown in Figure 13), which all solid particle 102 removal while maintaining the pressure in the PFB HX 111. The exemplary gas distributor 175 evaluated also had 16 orifices (i.e., holes) punctured through its surface to accommodate cyclone
30 dip-legs (not shown) to provide structural support for the cyclones.

Particle-gas separation is important for cleaning the gas 110 prior to the gas 110 reaching the turbine 103; solid particles 102 entering the turbine 103 shorten the life of the turbine 103 blades. In some embodiments of the present disclosure, solid particle 102 separation from gas 110 may include three stages: gravitational disengagement, impingement separation using a U-beam separator, and/or one or more nozzles 180 (i.e., cyclones). By placing the nozzles 180 within the high-temperature inner shell 155 of the PFB HX 111, the system is greatly simplified by eliminating the need for a separate vessel that contains just the nozzles 180. As a result, the nozzles 180 will be operated at high temperatures, so the design of a nozzle 180 may include refractory materials to withstand the high operating temperatures and abrasive conditions. They nozzle 180 may be supported by the inner shell. Figure 1C, after the solids have been removed from the gas and exit, the clean gas 110 may then exit the PFB HX 111 through the inner tube of the PIP 170 gas line to be subsequently directed to the turbine 103 for electricity generation. In some embodiments, a second particle filter may be external to the PFB HX 111 and upstream of the turbine 103 to further reduce the solid particle 102 concentration in the gas stream 110 and to protect the turbine 103 from erosion. This filter may be a high temperature ceramic candle filter.

Figure 10 illustrates a second exemplary gas distributor 175, according to some aspects of the present disclosure. The gas distributor 175 shown in Figure 10 is a large head pipe 186 with a plurality of manifold pipes 187 extending from the head pipe 186. The example shown in Figure 10 shows the manifold pipes 187 approximately perpendicular to the head pipe 186, but any orientation of the manifold pipes 187 may be used. In some embodiments, the head pipe 186 may have an outer diameter of approximately 2 inches, an inner diameter of approximately 1.75 inches, and a wall thickness (or pipe thickness) of approximately 1/8 inch. The manifold pipes 186 may have an outer diameter of approximately 5/16 inches, an inner diameter of approximately 0.215 inches, and a wall thickness of approximately 0.049 inches. The example gas distributor 175 in Figure 10 includes 284 orifices in total on the manifold pipes 187 and head pipe 186. The orifices have a diameter of approximately 3/32 inches. The gaps between the manifold pipes 187 allow the solid particles 102 to flow (or fall) down through the manifold pipes 187 and exit the PFB HX 111.

A total of sixteen (16) nozzles 180 (i.e., cyclones) were included in the exemplary PFB HX 111 described herein. They were all arranged to connect with the refractory layer of the inner shell 155 for structural purposes. As shown in Figure 11, nozzles 180 may be arranged in four sets of four. In some embodiments of the present disclosure, each set of four may be positioned as close

together as possible without physically touching. The incoming hot solid particles 102 are fed into the fluidized-bed 150 through the gaps formed by the sets of four nozzles (180). The gaps are designed to allow unobstructed flow of the solid particles 102 into the fluidized-bed 150. The collected cooled solid particles 102 fall through each nozzle's 180 dip-leg (not shown) to be
5 directed to small slots positioned in each dip-leg and a cone which directs the collected solid particles 102 out of the nozzle 180 and into the solid particle 102 outlet funnels that are incorporated into the gas distributor 175 described above.

For reliable transfer of hot solid particles 102 to a PFB HX 111, a lock hopper 190 (as shown in Figure 12) may be utilized to seal the pressurized gas 110 inside the PFB HX 111 and to enable
10 supplying gas 110 to a turbine 103 for electricity generation. A lock hopper 190 may have two valves: one located on the top of the lock hopper 190 for the gravitational flow of solid particles 102 from a storage silo 101 (not shown in Figure 12) into the lock hopper 190, and another located at the bottom of the lock hopper 190 for the gravitational flow of particles out of lock hopper 190 and into the PFB HX 111. After solid particles 102 have filled the lock hopper 190 to its capacity,
15 the top valve is closed, pressurized gas 110 enters the lock hopper 190 to pressurize the inside to a same pressure as the PFB HX 111. Then the bottom valve opens to release the solid particles 102 into the PFB HX 111. Thus, the two valves operate together to enable the dispensing of solid particles 102 into the PFB HX 111. Thus, in some embodiments of the present disclosure, at least two lock hoppers 190 may be needed to continuously feed hot solid particles 102 into the PFB HX
20 111; e.g., while one is filling, a second is feeding. Figure 12 illustrates a schematic of a solid particle feeding system utilizing a lock hopper 190, according to some embodiments of the present disclosure. Cooled gas 110A enters the PFB HX 111 from the turbine 103 and/or generator 104 and heated gas 110B exits the PFB HX 111.

Thus, a lock hopper 190 operates at two different pressure levels and two corresponding operating
25 conditions; charging, which corresponds to heating solid particles 102 using the particle heater 108, and discharging, which corresponds to cooling the solid particles 102 in the PFB HX 111. During discharge, the solid particles 102 being stored in the silo 101 and dispensed to the PFB HX 111 via a lock hopper 190 are extremely hot (e.g., about 1200 °C or greater). These hot solid particles 102, in some embodiments, may flow by gravity into the PFB HX 111 at rates as high as
30 300 kg/s, where, as described above, heat is transferred from the solid particles 102 to the gas 110. When in the other condition, when the system charging, the silo 101 is discharging cold solid

particles 102 at about 300 °C to a skip hoist 195 to be subsequently lifted and transferred to the particle heater. Thus, because of the two operating conditions, the insulation for the lock hopper 190 positioned at a silo 101's exit should be designed to minimize heat losses when operating at the high temperatures, e.g., about 1200 °C. For continuous operation, during discharging, to operate at a flow rate of about 300 kg/s requires the lock hopper 190 to discharge solid particles 102 at this same rate 300 kg/s to the PFB HX 111. Similarly, during charging, the solid particle 102 flow rate may need to be greater than 300 kg/s considering the skip hoist 195 traveling time. To satisfy these variable operating conditions, the lock hopper 190 valves (e.g., gate valves) need to be designed to operate at both the high temperature and the low temperature, e.g., a range between about 300 °C and about 1200 °C. In some embodiments of the present disclosure, the lock hopper 190 valves may be adjusted to a specific percent open, to provide finer control of the solid particle 102 flow from the silos 101. The valves may be made of a refractory material. Solid particles 102 exiting a PFB HX 111 through a lock hopper 190 may be redirected back to a silo 101, bypassing the particle heater 108. In some embodiments of the present disclosure, cold solid particles 102 may be positioned for storage on top of hot solid particles 102 in the same silo 101. When charging, the cold solid particles 101 bypass the PFB HX 111 and are transported to the skip hoist 195 for transport to the particle heater 108.

In some embodiments of the present disclosure, the materials of construction for a lock hopper 190 may be selected as follows, from inside to outside: a refractory and internal insulation within a structure steel shell, and external mineral wool for insulation from the ambient. Table 4 shows the metrics for such an exemplary lock hopper 190. For the example system described herein, the locker hopper 190 will operate under pressures of about 1.25 MPa.

Table 4: Exemplary lock hopper metrics.

Specification	Unit	Value
Lock Hopper Inlet Port Size	m	0.5
Lock Hopper Outlet Port Size	m	0.380
Lock Hopper Height	m	18
Particle Load of Single Lock Hopper	ton	63.81

In some embodiments of the present disclosure, particles may be directed into a PFB HX 111 from a single point positioned in the side wall of the outer shell 160. This flow of solid particles 102 should be distributed evenly across the cross section of inner shell containing the fluidized-bed

150 portion of the PFB HX 111. Among other things, such an even distribution of the solid particles 102 will prevent gas 110 from bypassing the solid particles 102. In the exemplary design described herein, a standpipe (not shown) is used into which the hot solid particles 102 will overflow to then drop through dip-leg pipes (not shown) to drop into the fluidized-bed 150.

- 5 As described above, a pipe-in-pipe (PIP) 170 may be used to direct gas 110 to and from a PFB HX 111. One advantage of a PIP 170 design is that it can yield significant savings on the insulation materials. The hot gas flows inside the inner pipe. This inner pipe may be insulated from the cold gas flowing through the annulus between the inner tube and the outer pipe. An insulation layer placed inside the inner pipe can lower the exterior temperature of the inner shell sufficiently to be
- 10 close to the temperature of the cool gas flowing through the annulus (e.g., about 300 °C). Therefore, conventional steel can be used for both the inner and outer pipes. This PIP 170 gas line configuration also means the inner pipe is subjected to nearly equal pressure between the hot and cold gases 110, thus reducing wall thicknesses and cost. The outer pipe may be insulated to prevent heat loss from the entering gas 110 to the environment. A PIP gas-line 170 design is illustrated in
- 15 Figure 13, according to some embodiments of the present disclosure.

The cross section of the PIP gas-line 170 indicates that the high temperature gas 110 flows through the inner pipe, and the low temperature gas through the annular space created by the positioning the inner pipe inside the outer pipe. The two gas 110 flows flow counter-current to one another. In some embodiments of the present disclosure, both inside pipe and outer pipe may be insulated with

20 insulated as shown in Figure 13. For each gas turbine unit, the connecting pipeline is designed as a pipe bundle to deliver the required amount of gas flow between the power system and the PFB HX 111 within the desired pressure drop. Low-temperature gas 110 from the compressor fed to the annular space helps to cool the outer pipe, thus enabling both pipes to be constructed of carbon steel.

- 25 The inner pipe in Figure 13 may be configured to transport heated gas 110 at a temperature of approximately 1200 °C. In the example shown in Figure 14, the inner pipe may have an inner diameter of approximately 1.650 m and be insulated with GUNCAST ® 28 LI in a thickness of about 0.165 m, INSULMIX ® C2035 LI in a thickness of about 0.300 m, and an A36 steel shell with a thickness of about 00.08 m (or approximately 5/16 inches). The outer pipe in Figure 14 may
- 30 be configured to transport cooled gas 110 at a temperature of approximately 300 °C and/or within

the range of about 200 °C to about 600 °C. In the example shown in Figure 14, the outer pipe may have an inner diameter of about 2.850 m, an A36 steel shell of about 0.034 m, and mineral wool of about 0.100 m. In some embodiments, the outer pipe may have an inner diameter in the range of about 0.1 m to about 10 m. In some embodiments, the inner pipe may have an inner diameter in the range of about 0.1 m to about 10 m.

In some embodiments, the heat transfer within the PFB HX 111 may be from heated gas 110 to solid particles 102, which then heats the solid particles 102 and cools the gas 110. This may be for heat gas 110 exiting the turbine 103 to allow for pumped thermal energy storage. In such an embodiment, the heated gas 110 may flow through the outer annulus (i.e., outer pipe) of the PIP gas line 170 and the cooler gas 110 may flow through the interior annulus (i.e., inner pipe) of the PIP gas line 170. The direction of the gas 110 flow may be counter-current to the flow of the solid particles 102.

The foregoing discussion and examples have been presented for purposes of illustration and description. The foregoing is not intended to limit the aspects, embodiments, or configurations to the form or forms disclosed herein. In the foregoing Detailed Description for example, various features of the aspects, embodiments, or configurations are grouped together in one or more embodiments, configurations, or aspects for the purpose of streamlining the disclosure. The features of the aspects, embodiments, or configurations may be combined in alternate aspects, embodiments, or configurations other than those discussed above. This method of disclosure is not to be interpreted as reflecting an intention that the aspects, embodiments, or configurations require more features than are expressly recited in each claim. Rather, as the following claims reflect, inventive aspects lie in less than all features of a single foregoing disclosed embodiment, configuration, or aspect. While certain aspects of conventional technology have been discussed to facilitate disclosure of some embodiments of the present invention, the Applicants in no way disclaim these technical aspects, and it is contemplated that the claimed invention may encompass one or more of the conventional technical aspects discussed herein. Thus, the following claims are hereby incorporated into this Detailed Description, with each claim standing on its own as a separate aspect, embodiment, or configuration.

CLAIMS

What is claimed is:

1. A heat exchanger configured to transfer thermal energy between a gas stream and a stream of solid particles, the heat exchanger comprising:

5 a means for contacting the gas stream with the stream of solid particles resulting in a transfer of thermal energy between the gas stream and the stream of solid particles; wherein the heat exchanger is configured to gravitationally pass the stream of solid particles through the means for contacting, and

10 the heat exchanger is configured such that the gas stream flows counter-current to the stream of solid particles.

2. The heat exchanger of claim 1, further comprising:

an outer shell; and

an inner shell, wherein:

15 the means for contacting is positioned within the inner shell.

3. The heat exchanger of claim 2, further comprising a gas inlet configured to direct the gas stream to the means for contacting.

20 4. The heat exchanger of claim 3, further comprising a gas outlet configured to receive the gas stream from the means for contacting.

5. The heat exchanger of claim 4, wherein:

the gas stream has a temperature, and

25 the temperature is substantially greater at the gas outlet than at the gas inlet.

6. The heat exchanger of claim 4, wherein:

the gas stream has a temperature,

30 the temperature is substantially lower at the gas outlet than at the gas inlet.

7. The heat exchanger of claim 4, wherein:
the gas inlet comprises a first pipe,
the gas outlet comprises a second pipe,
the second pipe is positioned concentrically within the first pipe creating a first annular
5 space, and
the gas stream is configured to flow through the first annular space.

8. The heat exchanger of claim 7, wherein:
the inner shell is positioned within the outer shell creating a second annular space, and
10 the gas stream is configured to flow from the first annular space to the second annular
space.

9. The heat exchanger of claim 1, further comprising:
a means for distributing the gas stream through the means for contacting, wherein:
15 the means for distributing is positioned before the means for contacting, relative to the
direction of flow of the gas stream through the heat exchanger.

10. The heat exchanger of claim 9, wherein:
the means for distributing comprises a plate having an orifice, and
20 the orifice is connected to a bubble cap.

11. The heat exchanger of claim 1, further comprising:
a means for directing the solid particles stream to the means for contacting, wherein:
the means for directing is positioned before the means for contacting, relative to the
25 direction of flow of the stream of solid particles through the heat exchanger.

12. The heat exchanger of claim 1, wherein:
the means for contacting results in a portion of the stream of solid particles entrained within
the gas stream.
30

13. The heat exchanger of claim 12, further comprising:
a means for separating the stream of solid particles from the gas stream.
14. The heat exchanger of claim 13, wherein:
5 the means for separating comprises a nozzle having an inlet, a first outlet, and a second outlet,
the inlet is configured to receive the gas stream and the stream of solid particles,
the first outlet is configured to release the gas stream from the nozzle, and
the second outlet is configured to release the gas stream from the nozzle.
- 10 15. A method for converting thermal energy to electrical energy, the method comprising:
transferring thermal energy from a plurality of solid particles to a gas stream using a heat exchanger; and
using the gas stream to spin a turbine to generate electrical energy; wherein;
15 the heat exchanger comprises:
an outer shell;
an inner shell positioned within the outer shell and having an internal volume;
an annular space between the inner shell and the outer shell configured to allow
the gas stream through the annular space;
20 a pipe-in-pipe (PIP) gas line configured to direct the gas stream to the annular space; and
a first port that penetrates the inner shell and the outer shell configured to direct the plurality of solid particles into the internal volume; wherein:
the gas stream exits the annular space to pass through a distribution plate and into
25 the internal volume,
the internal volume is configured to contact the gas stream with the plurality of solid particles,
the heat exchanger is configured such that the plurality of solid particles flow gravitationally through the internal volume to a second port located in the distribution plate
30 configured to remove the plurality of solid particles from the heat exchanger,

the heat exchanger is configured such that the gas flows counter-current to the plurality of solid particles to enter an upper portion of the internal volume, which is configured to separate the plurality of solid particles from the gas stream, and

the PIP gas line is configured to remove the gas stream from the heat exchanger.

5

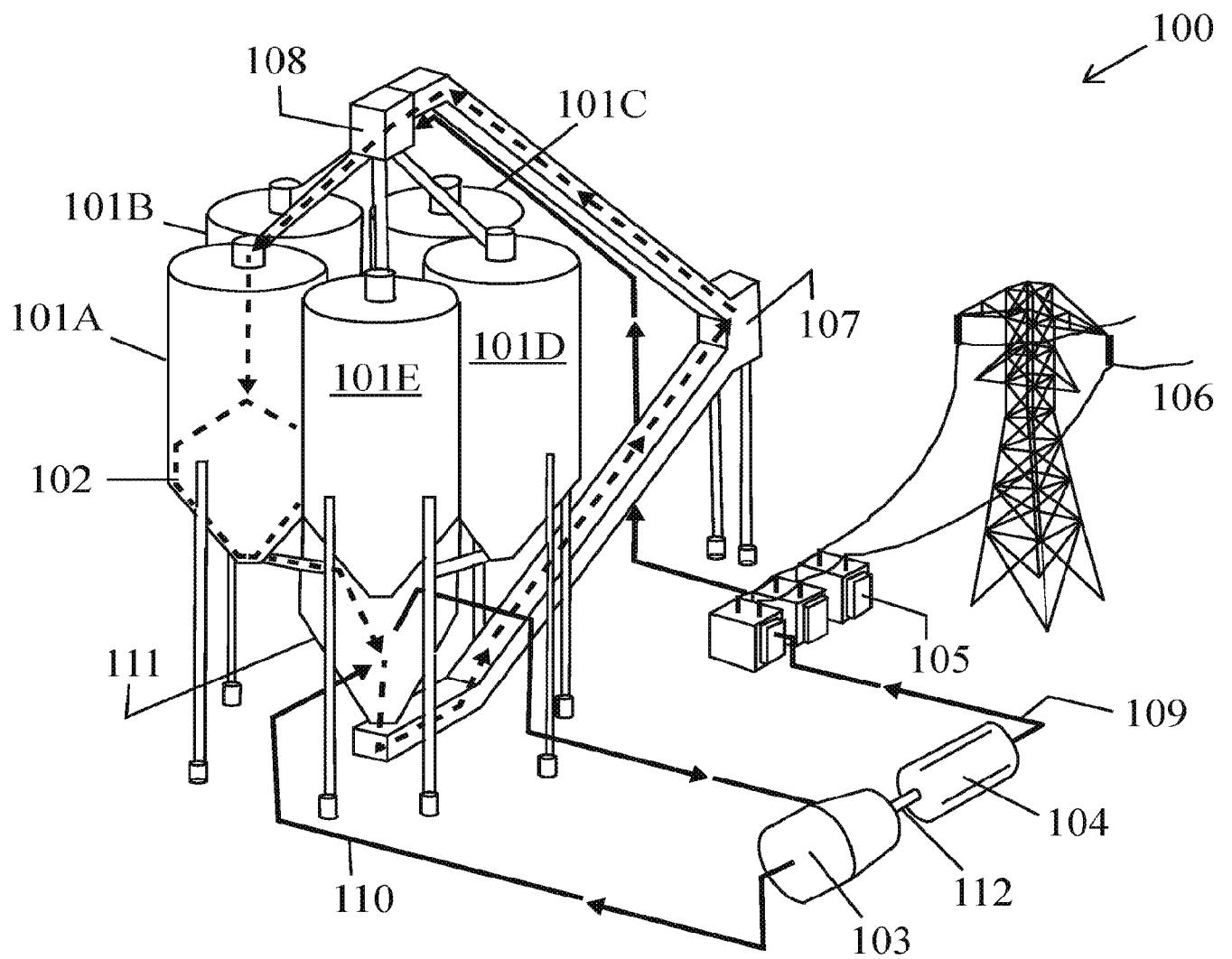


Figure 1A

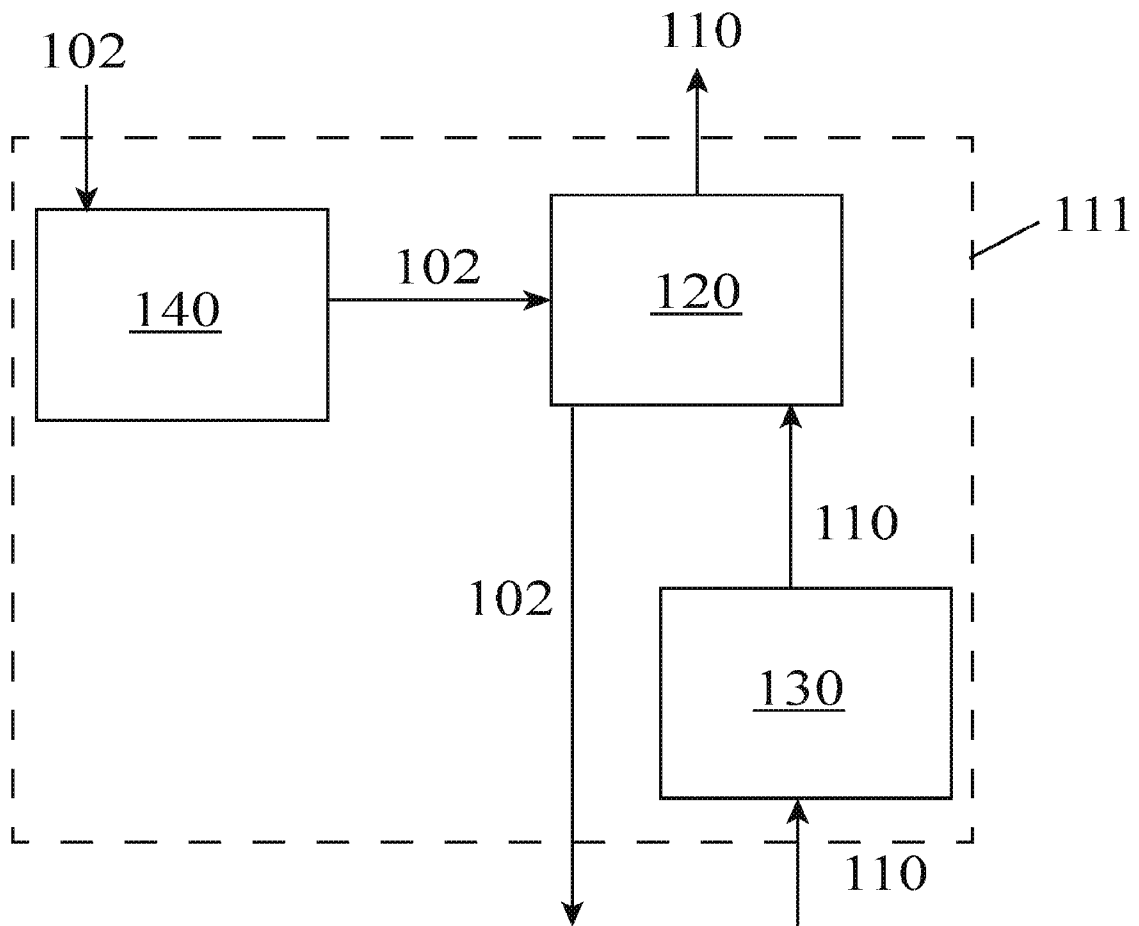


Figure 1B

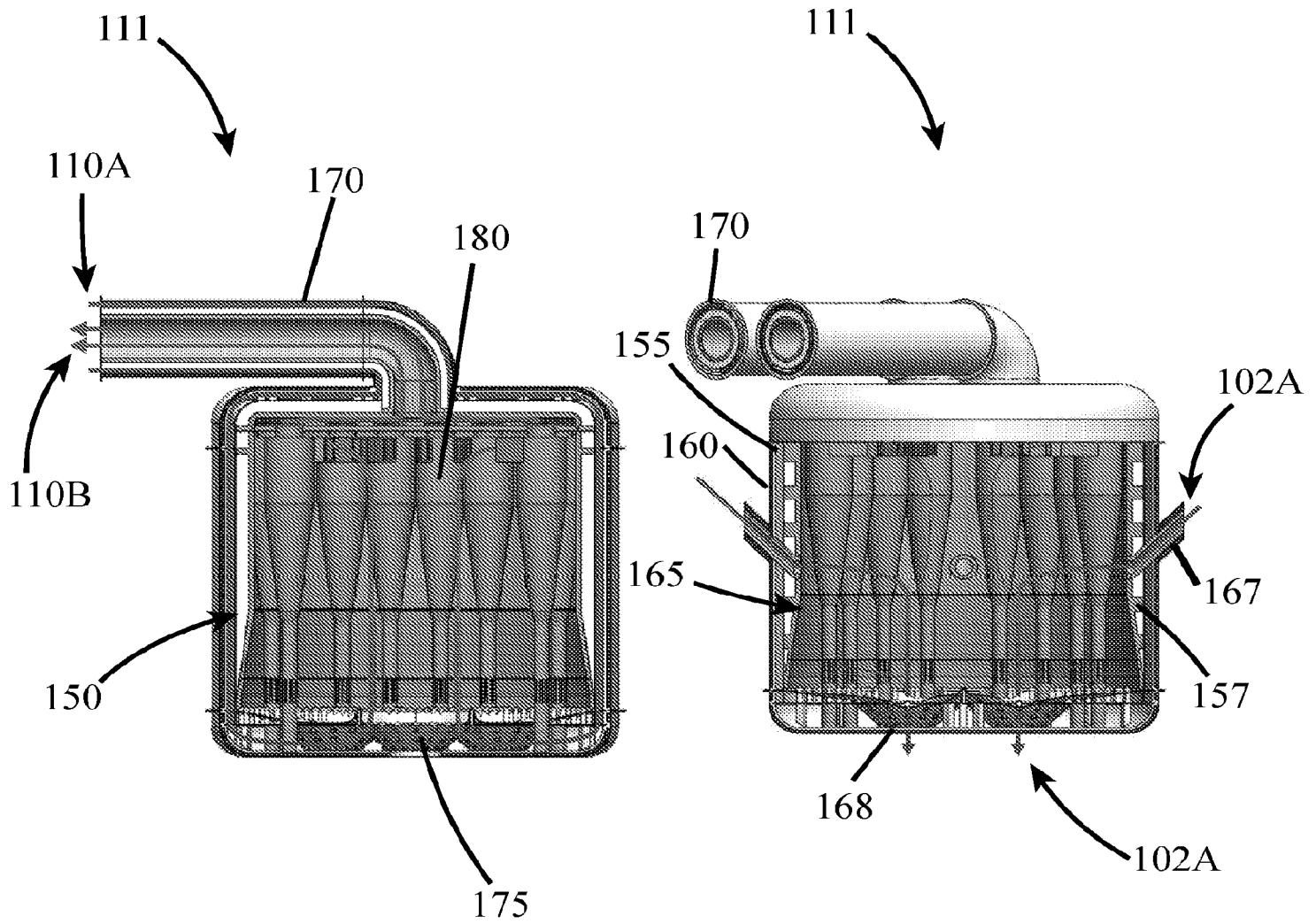


Figure 1C

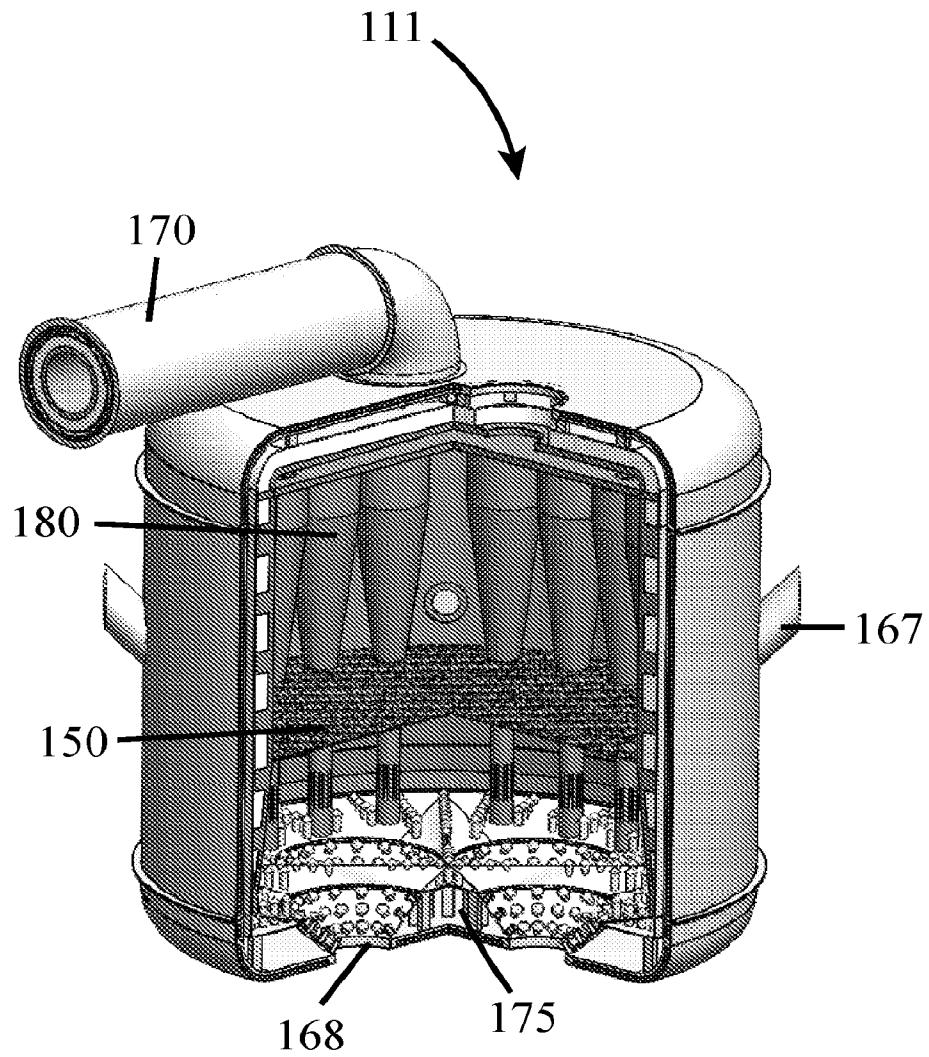


Figure 2

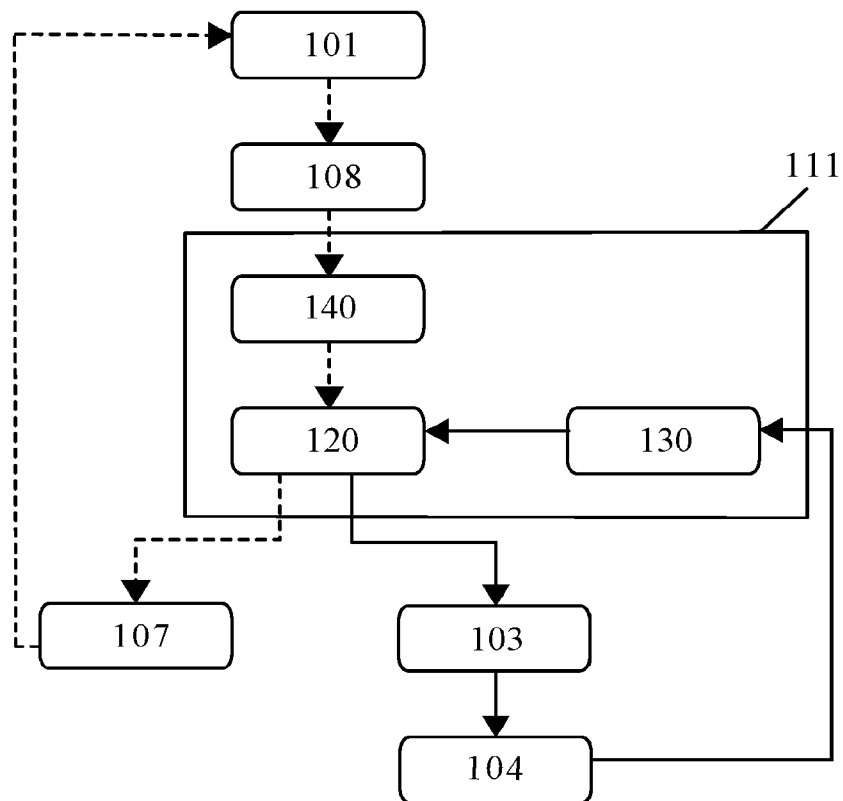


Figure 3

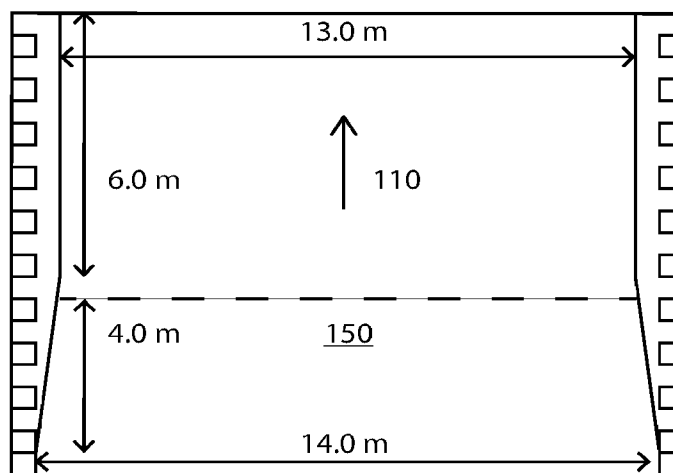


Figure 4

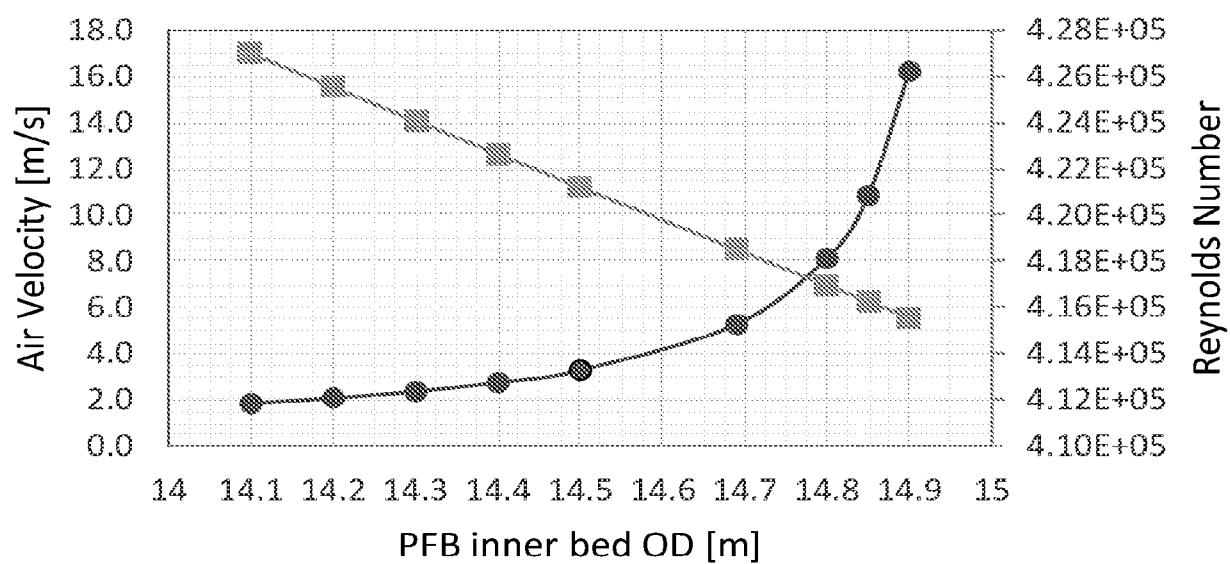


Figure 5

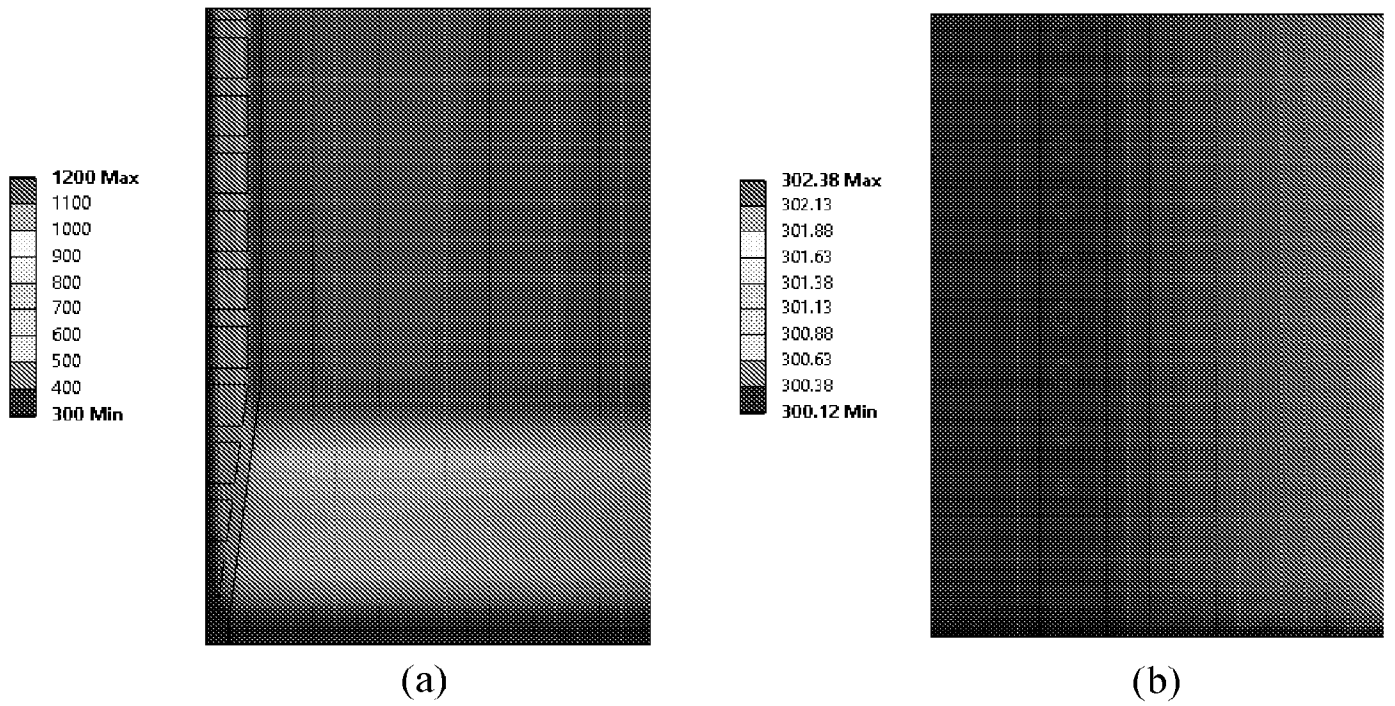


Figure 6

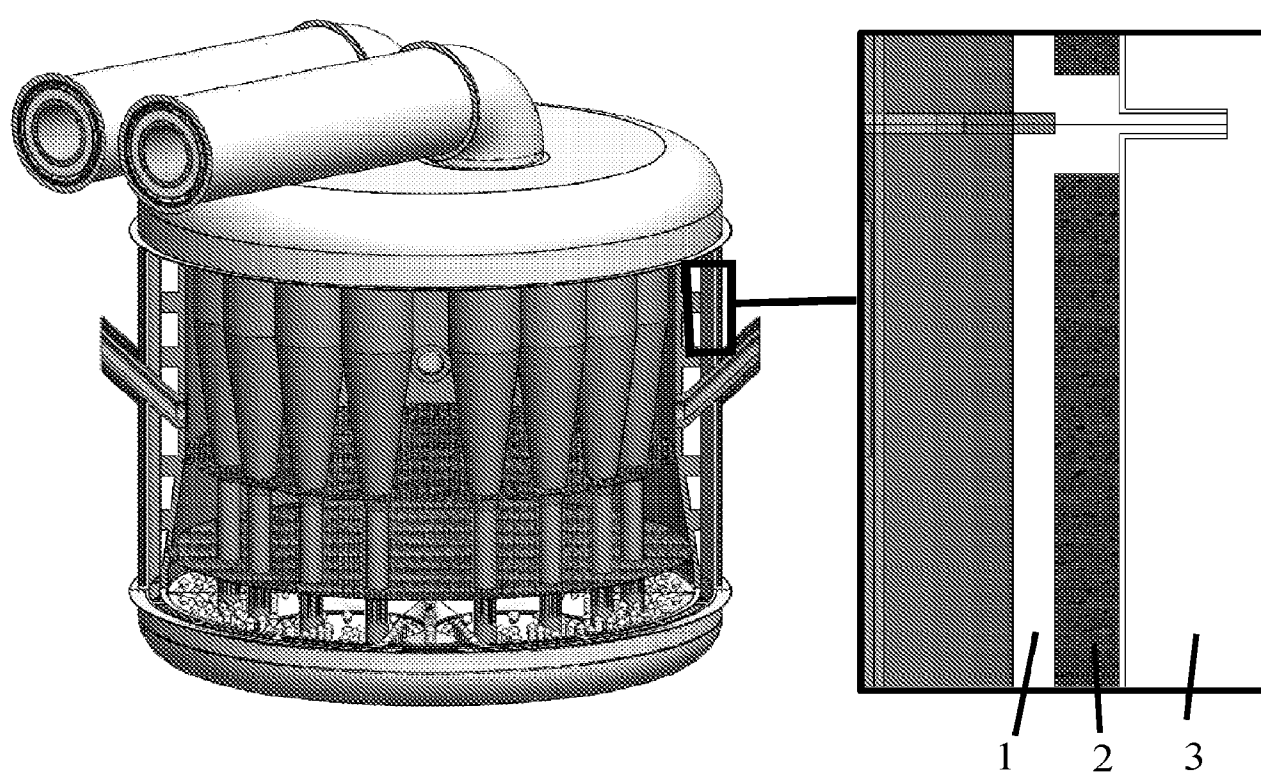


Figure 7

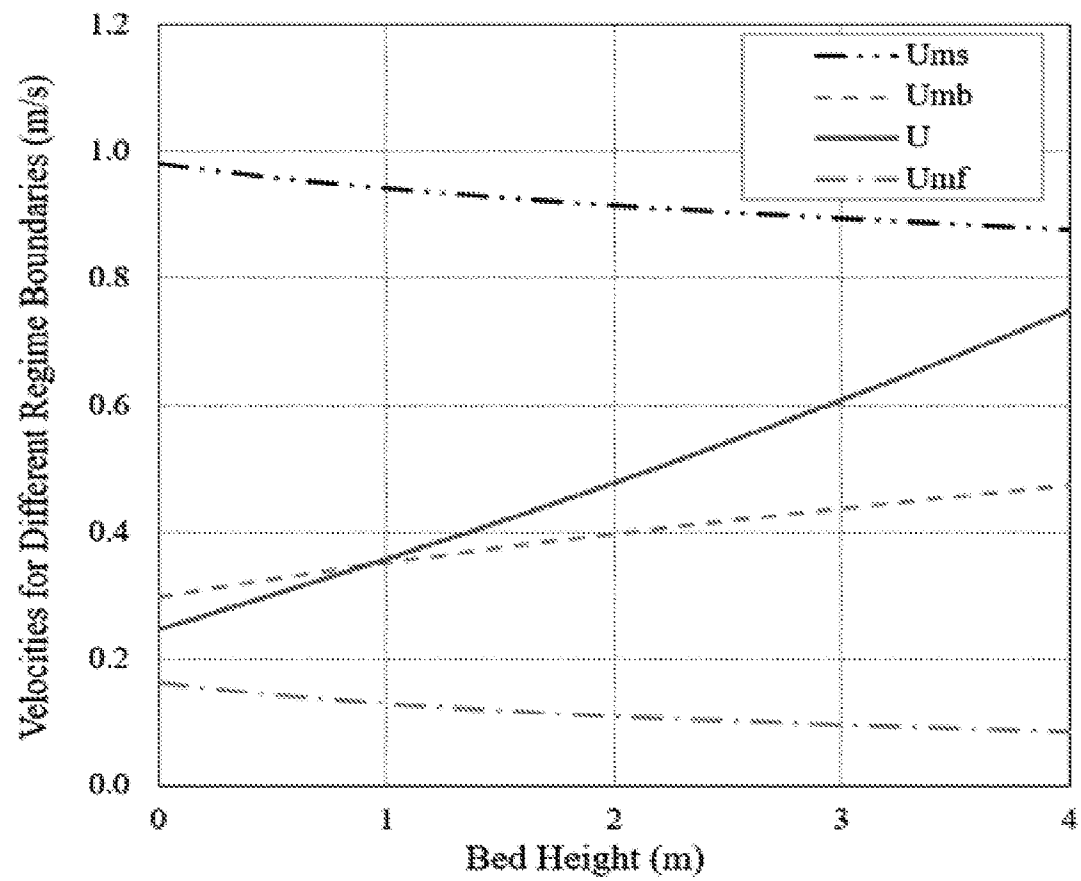


Figure 8

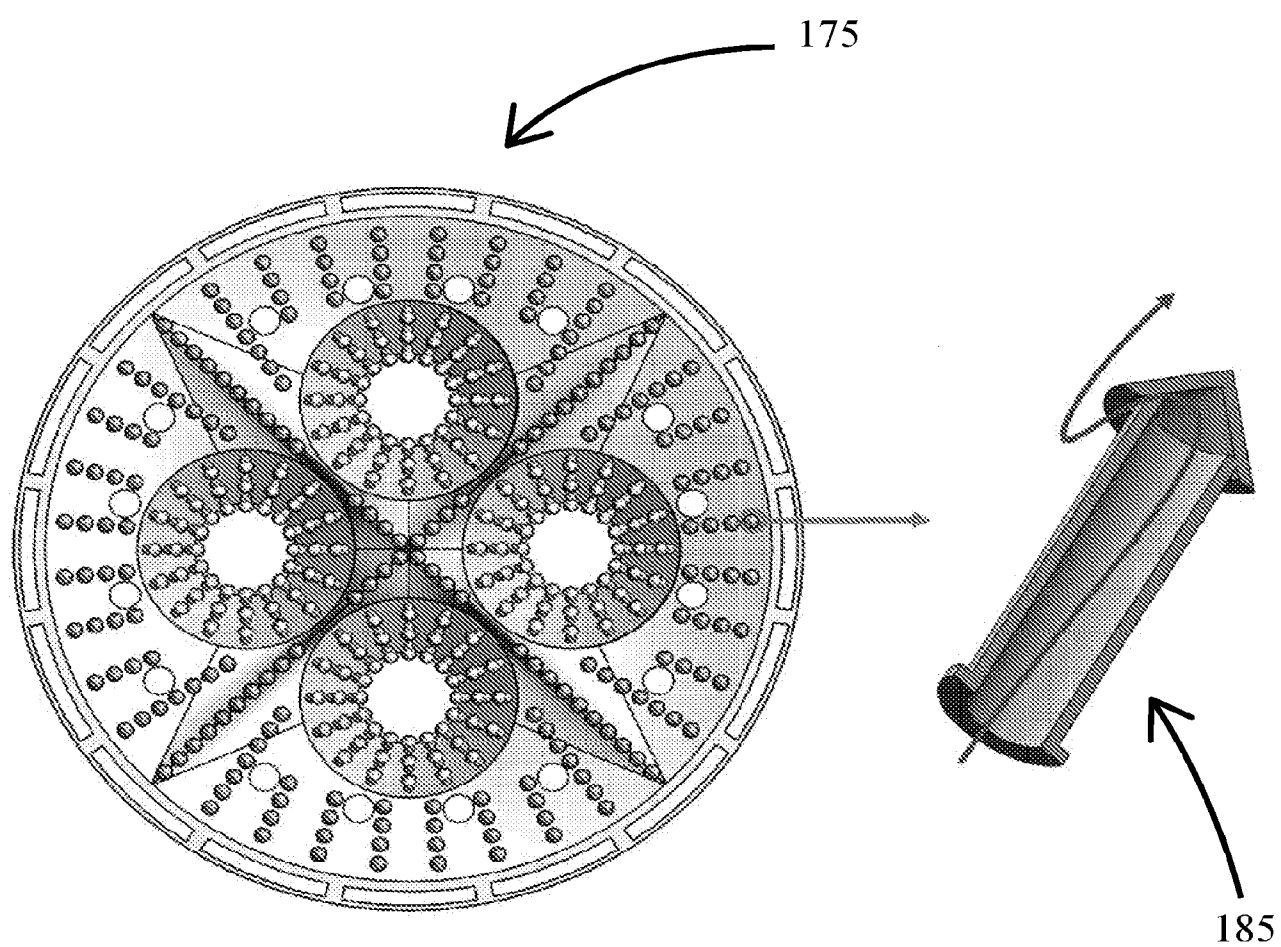


Figure 9

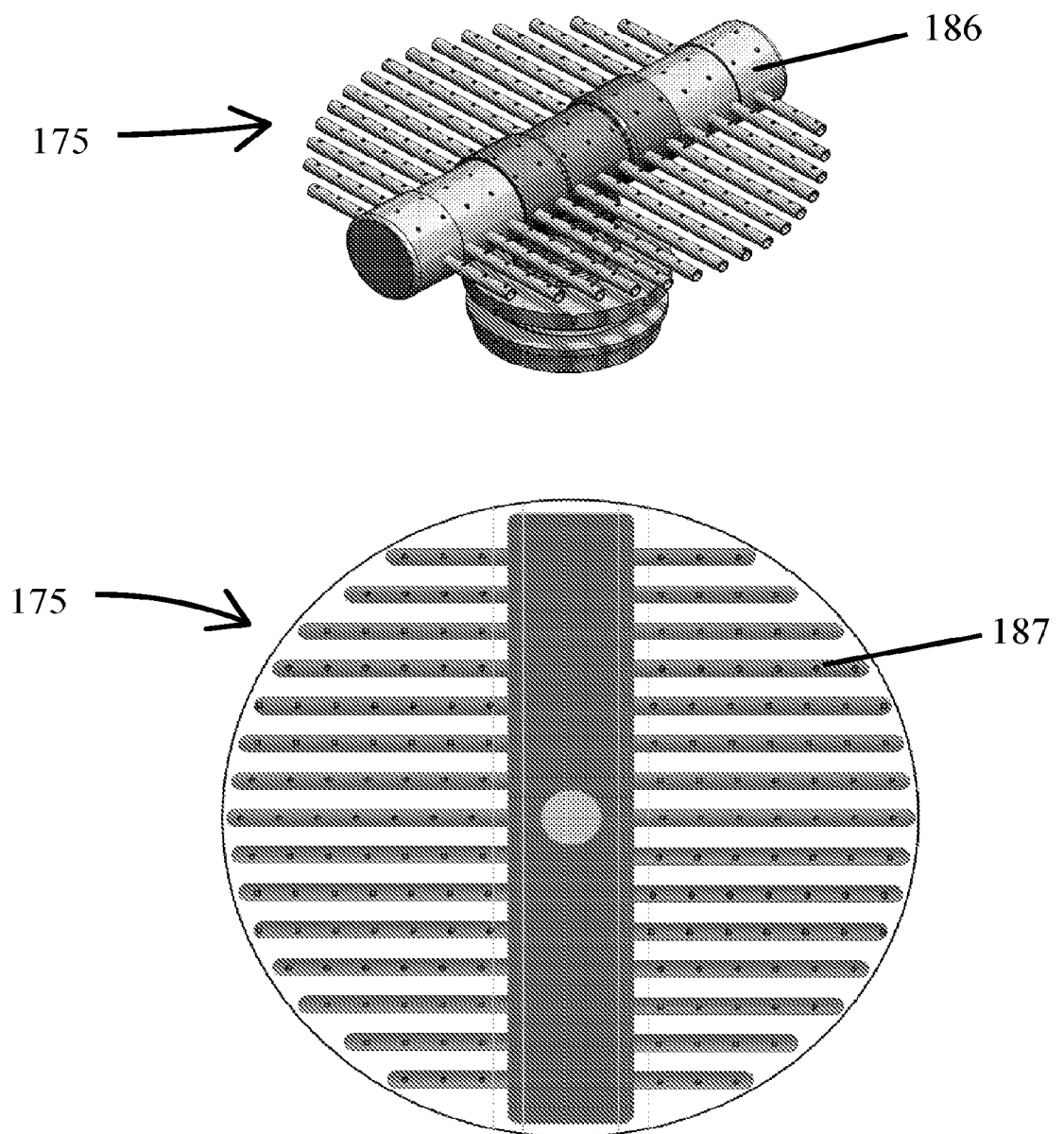


Figure 10

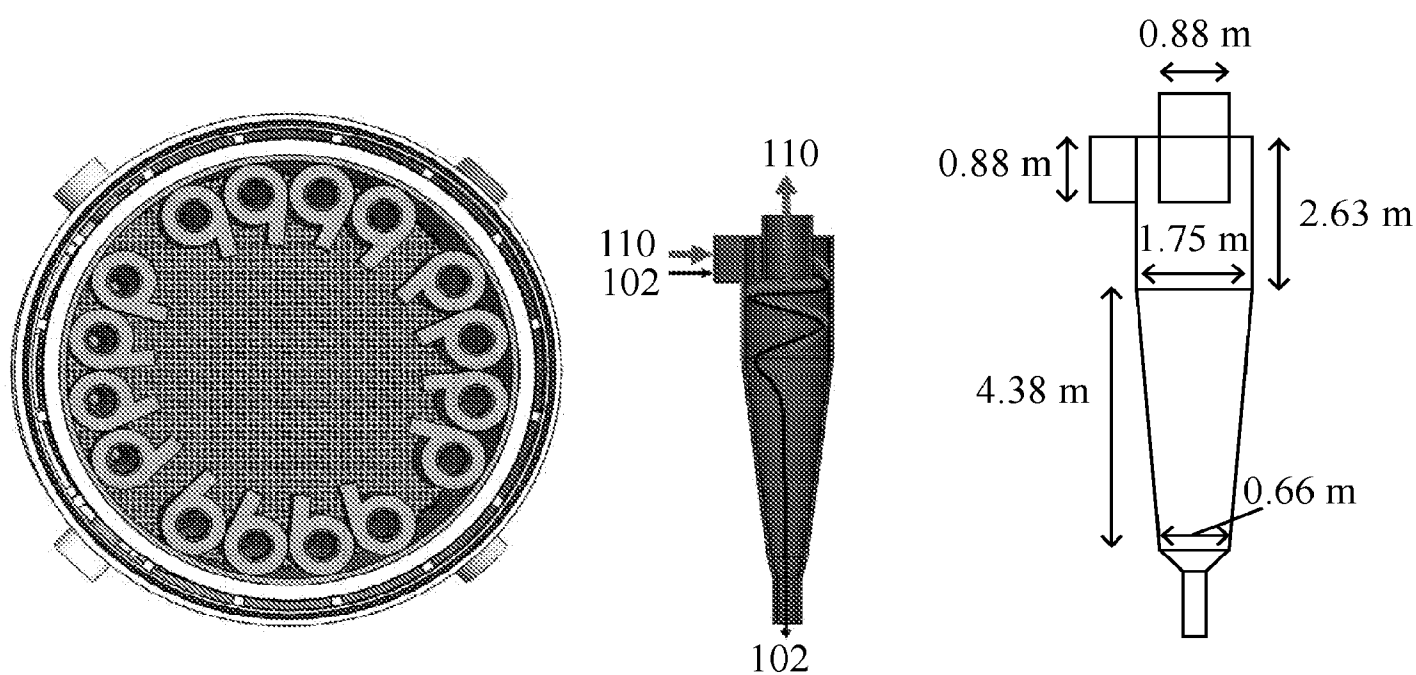


Figure 11

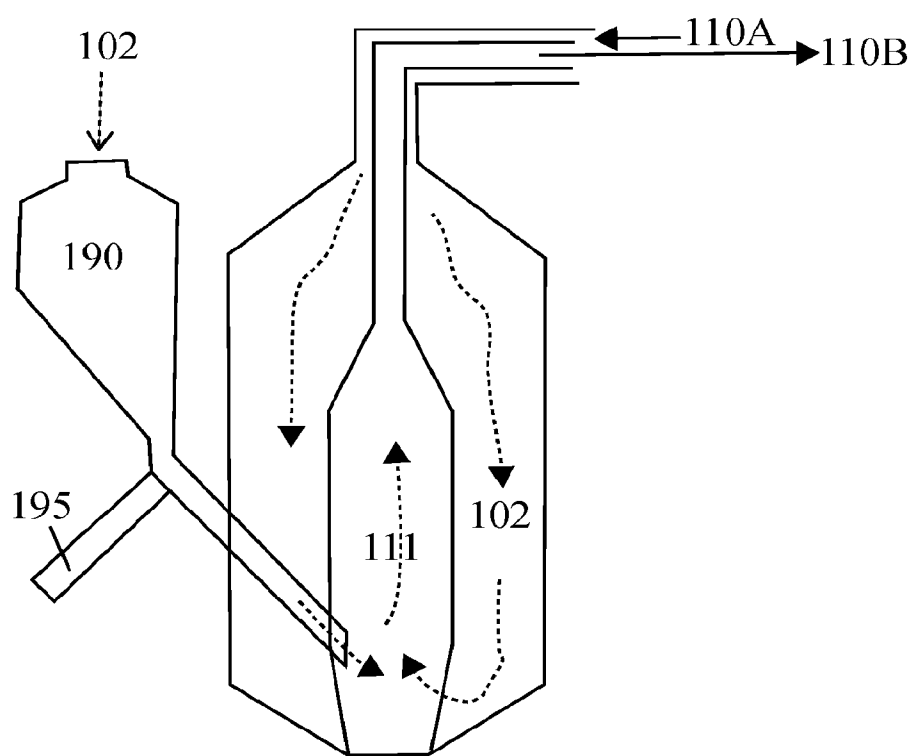


Figure 12

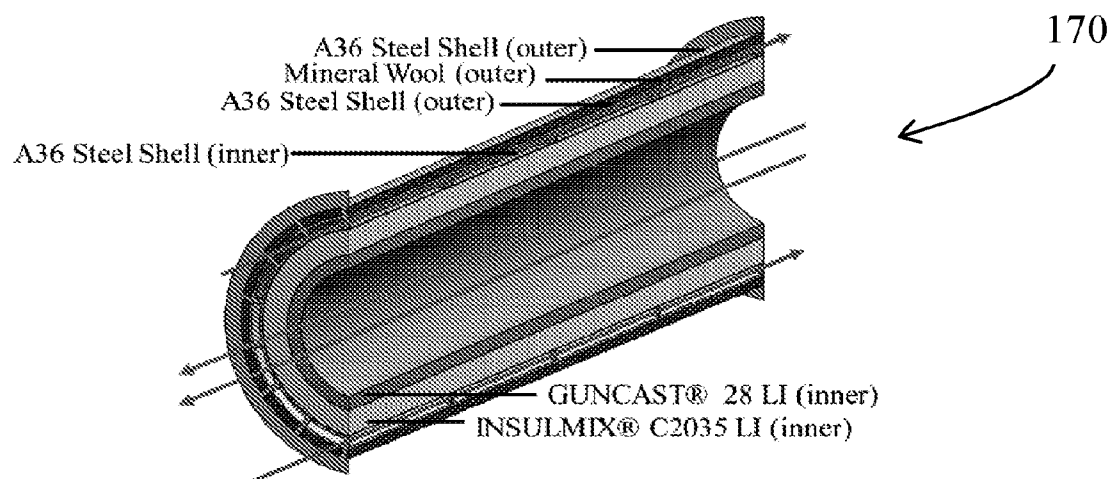


Figure 13