



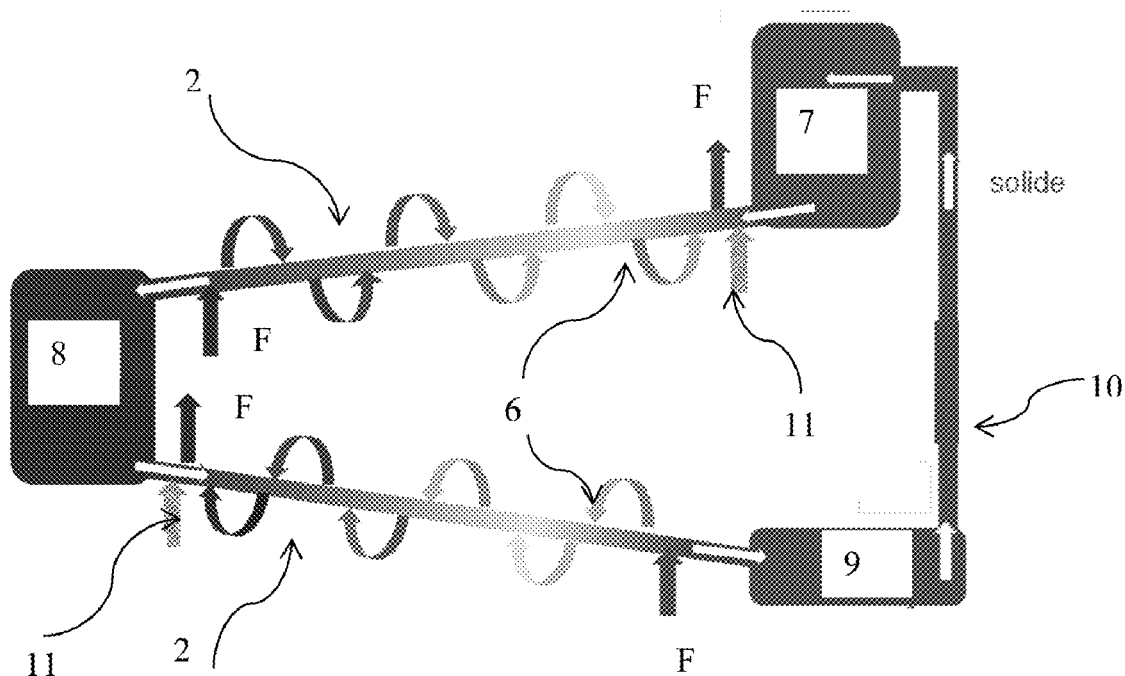
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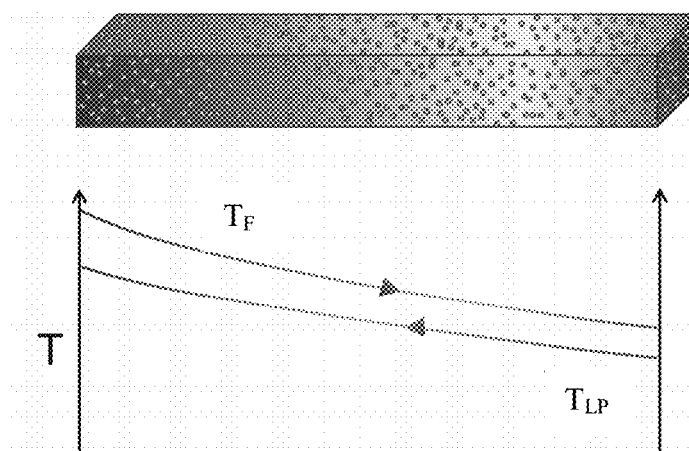
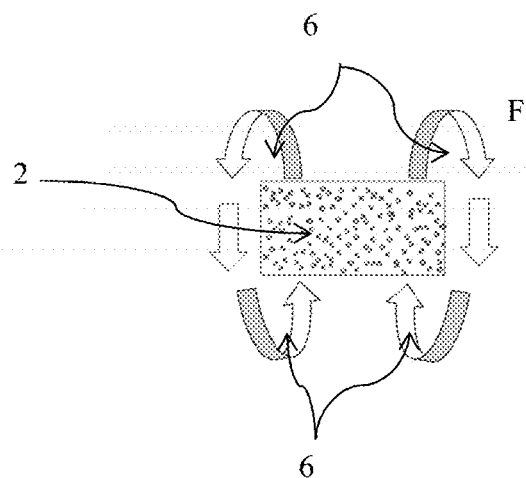
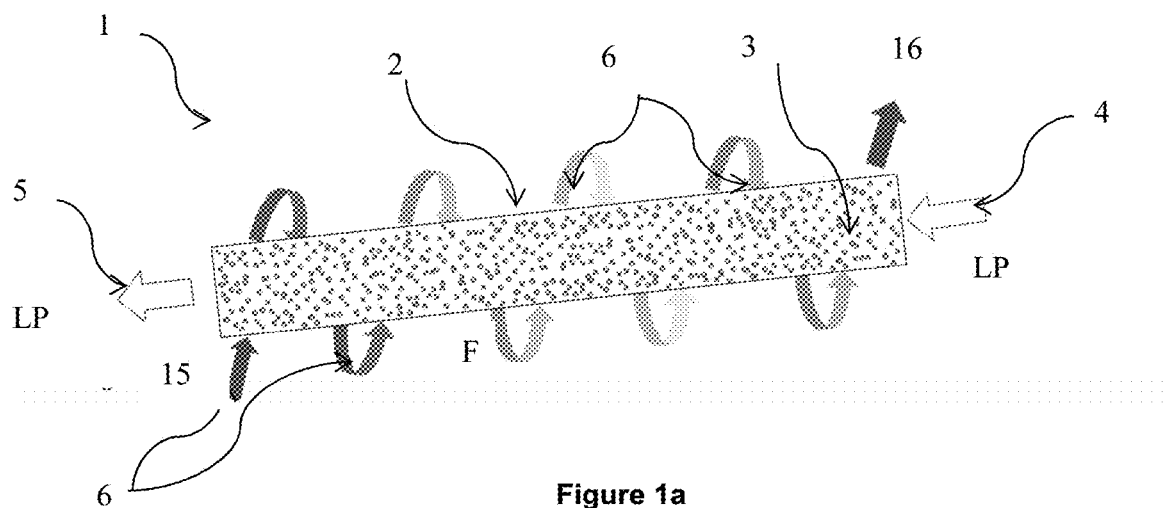
(19) **United States**(12) **Patent Application Publication**
PLAIS et al.(10) **Pub. No.: US 2017/0159503 A1**(43) **Pub. Date: Jun. 8, 2017**(54) **SYSTEM AND METHOD FOR THE
CROSSFLOW EXCHANGE OF HEAT
BETWEEN A FLUID AND HEAT STORAGE
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Willi NASTOLL, LYON (FR)**(21) Appl. No.: **15/372,138**(22) Filed: **Dec. 7, 2016**(30) **Foreign Application Priority Data**

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(2013.01)(57) **ABSTRACT**

The present invention relates to a system and a method for exchanging heat between a fluid (F) and heat storage particles (3). The exchange system comprises an exchange zone (2) in which the fluid (F) and the heat storage particles in a fluidized bed flow as a countercurrent flow and a cross flow. The invention also relates to a compressed gas energy storage and restoration system and method using the heat exchange system.





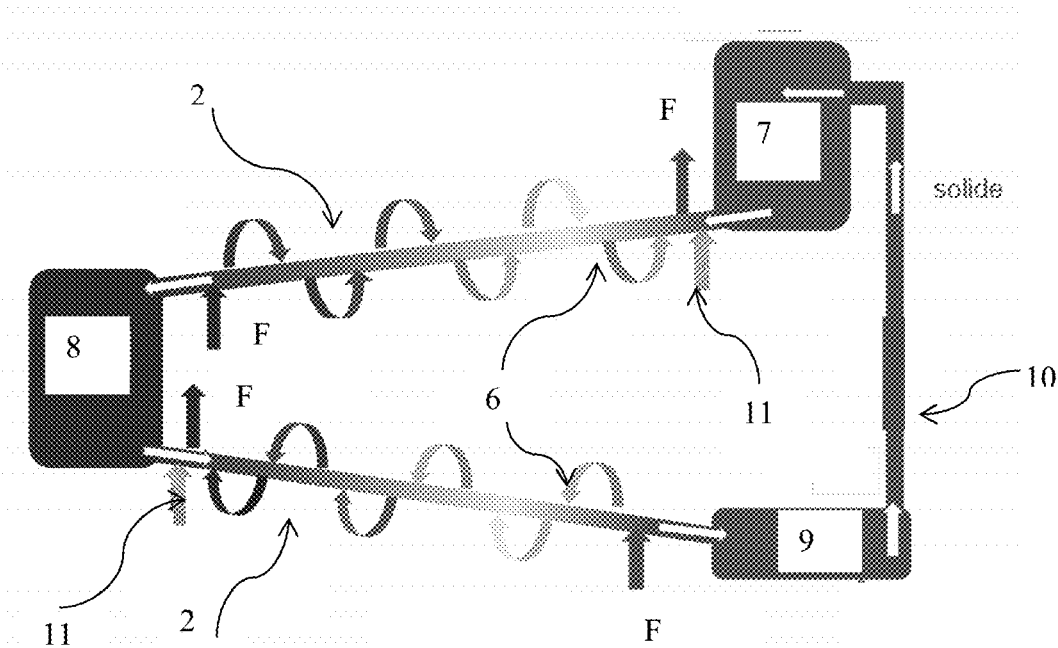


Figure 3

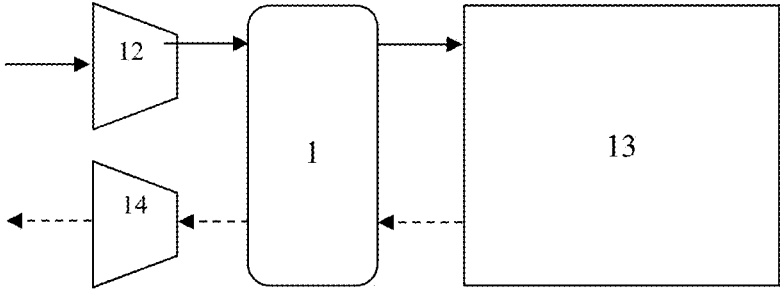


Figure 4

SYSTEM AND METHOD FOR THE CROSSFLOW EXCHANGE OF HEAT BETWEEN A FLUID AND HEAT STORAGE PARTICLES

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] Reference is made to French Patent Application no. 15/61.932 filed Dec. 7, 2015, which is incorporated herein by reference in its entirety.

BACKGROUND OF THE INVENTION

[0002] Field of the Invention

[0003] The present invention relates to heat exchange systems and particularly to storage of heat in a system or method of the AA-CAES (Advanced Adiabatic-Compressed Air Energy Storage) type.

[0004] Description of the Prior Art

[0005] In a compressed air energy storage (CAES) system, the energy, which is to be used at some other time, is stored in the form of compressed air. For storage, energy, notably electrical energy drives air compressors, and for release, the compressed air drives turbines, which may be connected to an electric generator. The efficiency of this solution is suboptimal because some of the energy of the compressed air is in the form of heat which is not used. Specifically, in CAES methods, only the mechanical energy of the air is used, which means that all of the heat produced at the time of compression is discarded. By way of example, air compressed to 8 MPa (80 bar) heats up during compression to around 150° C., but is cooled prior to storage. In addition, the efficiency of a CAES system is suboptimal because the system then requires the stored air to be heated in order to cause the air to expand. Specifically, if the air is stored at 8 MPa (80 bar) and ambient temperature, and if the energy is to be recuperated through an expansion, the decompression of the air once again follows an isentropic curve, but this time from the initial storage conditions (approximately 8 MPa and 300 K). The air therefore cools down to unrealistic temperatures (83 K which is -191° C.). It is therefore necessary to heat it, something which can be done using a gas burner or burner operating on some other fuel.

[0006] Several variants of this system currently exist. Particular mention may be made of the following systems and methods:

[0007] ACAES (Adiabatic Compressed Air Energy Storage) in which the air is stored at high temperature due to the compression. However, this type of system requires a special storage system that is bulky and expensive (adiabatic storage).

[0008] AACAES (Advanced Adiabatic Compressed Air Energy Storage) in which the air is stored at ambient temperature and the heat due to the compression is also stored, separately, in a heat storage system TES (Thermal Energy Storage). The heat stored in the TES is used to heat the air before it expands. According to certain envisioned designs, the heat is stored in the storage system using solid particles.

[0009] Moreover, such heat exchange systems are used in other fields: to store solar and marine energy, in metallurgy processes, etc.

[0010] One of the design criteria for heat storage and exchange systems is that they must be capable of controlling

the thermal stratification (thermocline) from low temperatures toward high temperatures. This is because the yield of heat and heat storage efficiency are dependent on this.

[0011] To this end, several types of heat exchange system have been developed. Certain types of heat exchange system relate to a fixed bed of solid particles, or exchanges of heat between fluids circulating concurrentwise. However, these exchanges of heat are suboptimal in terms of efficiency.

[0012] For example, patent applications WO 2011/027309 and WO 2011/135501 describe heat storage systems comprising solid particles in the form of a fluidized bed. However, with these solutions, the exchanges of heat between the fluid and the solid particles occur indirectly by a heat exchanger immersed in the fluidized bed. Thus, the effectiveness of the exchange of heat between the storage fluid and the solid particles is suboptimal, notably because the exchange of heat is indirect and because not all of the particles are in contact with the storage fluid.

[0013] In addition, French Patent Application No. 3004245 proposes several configurations of a thermal heat exchange system involving fluidizing particles by means of thermochemical reactions. However, that solution also entails a heat exchanger passing through the fluidized bed, which does not allow the exchange of heat to be optimized notably because the exchange is indirect and because not all of the particles are in contact with the fluid.

SUMMARY OF THE INVENTION

[0014] In order to alleviate these disadvantages, the present invention relates to a system for exchanging heat between a fluid and heat storage particles. The exchange system comprises an exchange zone in which the fluid and the heat storage particles (in the form of a fluidized bed) flow as a countercurrent flow and a cross flow. This countercurrent and cross-flow flow pattern allows the exchange of heat between the fluid and the particles to be highly effective.

[0015] The invention relates to a system for the exchange of heat between a fluid and heat storage particles comprising at least one heat exchange zone in which the fluid and a fluidized bed comprising the heat storage particles flow. The heat exchange system comprises apparatus for circulating the fluid which is configured to form a cross-flow circulation of the fluid with respect to the fluidized bed in the heat exchange zone and to cause the fluid to circulate from the outlet toward the inlet of the fluidized bed in the heat exchange zone.

[0016] According to one embodiment of the invention the apparatus for circulating the fluid comprises means for injecting and means for withdrawing the fluid which are able to cause the fluid to circulate in a direction substantially perpendicular to the circulation of the fluidized bed.

[0017] Advantageously, the apparatus for circulating comprises a plurality of injectors and means for withdrawing the fluid which are combined in such a way that the fluid circulates through each of the injectors and means for withdrawing consecutively. The injectors and the means of withdrawing are arranged consecutively along the heat exchange zone. The fluid coming from a means of withdrawing is introduced into the exchange zone by an injector situated upstream with respect to the circulation of the fluidized bed.

[0018] Preferably, the heat exchange zone is formed within a pipe.

[0019] According to an alternative form, the fluidized bed flows under in influence of gravity in the heat exchange zone.

[0020] Preferably, the heat exchange zone is inclined with respect to the horizontal.

[0021] According to one design of the invention, the particles comprise phase change materials.

[0022] According to one feature of the invention, the fluid circulates in a substantially upward path.

[0023] Advantageously the fluid is a gas, notably air.

[0024] According to one embodiment, the heat exchange system comprises at least two storage reservoirs for storing the heat storage particles and at least one heat exchange zone being located between the reservoirs.

[0025] According to an alternative form of this embodiment, the heat exchange system comprises a first storage reservoir for storing the particles, a second storage reservoir for storing the particles, at least one first heat exchange zone being formed between the first and second reservoirs and a third storage reservoir for storing the particles and at least one second heat exchange zone formed between the second and third reservoirs.

[0026] Advantageously, the system comprises means of transporting the heat storage particles from the third reservoir to the first reservoir.

[0027] Furthermore, the invention relates to a compressed gas energy storage and recovery system, comprising at least one gas compressor, at least one compressed gas storage, and at least one means for expanding the compressed gas in order to generate energy. The compressed gas energy storage and recovery system comprises at least one heat exchange system according to one of the preceding features.

[0028] In addition, the invention relates to a method for exchanging heat between a fluid and heat storage particles, in which the following steps are carried out for the heat exchange:

[0029] a) a fluidized bed comprising the heat storage particles is circulated in a heat exchange zone; and

[0030] b) the fluid is circulated in the heat exchange zone as a crossflow with respect to the fluidized bed, from the outlet toward the inlet of the fluidized bed in the heat exchange zone.

[0031] Advantageously, gravity contributes to the fluidized bed being circulated in the heat exchange zone.

[0032] According to one embodiment of the invention, the fluid is circulated in a direction substantially perpendicular to the direction of circulation of the fluidized bed.

[0033] According to an alternative form, the heat storage particles are stored in a first reservoir prior to the heat exchange, and the heat storage particles are stored in a second reservoir after the heat exchange.

[0034] Preferably, the following steps are carried out:

[0035] a) storing the heat storage particles in a first reservoir;

[0036] b) exchanging heat between the particles stored in the first reservoir and a fluid;

[0037] c) storing the particles leaving the heat exchange in a second reservoir;

[0038] d) performing the exchange of heat between the particles stored in the second reservoir and a fluid; and

[0039] e) storing the particles leaving the heat exchange in the first reservoir or in a third reservoir.

[0040] Preferably, the heat storage particles are transported from the third reservoir toward the first reservoir.

[0041] The invention also relates to a compressed gas energy storage and recovery method in which the following steps are performed:

[0042] a) compressing a gas;

[0043] b) cooling the compressed gas by exchange of heat in the heat exchange system of the invention;

[0044] c) storing the cooled gas;

[0045] d) heating the cooled compressed gas by addition of heat in the heat exchange system; and

[0046] e) expanding the heated compressed gas to generate energy.

BRIEF DESCRIPTION OF THE DRAWINGS

[0047] Further features and advantages of the system and of the method according to the invention will become apparent from reading the following description of nonlimiting exemplary embodiments, with reference to the attached figures described hereinbelow.

[0048] FIG. 1a illustrates, longitudinally, a heat exchange system according to one embodiment of the invention.

[0049] FIG. 1b illustrates, transversely, a heat exchange system according to one embodiment of the invention.

[0050] FIG. 2 represents the temperature of the fluid and of the particles within a heat exchange system according to one embodiment of the invention.

[0051] FIG. 3 depicts a heat storage system according to one embodiment of the invention.

[0052] FIG. 4 illustrates a compressed gas energy storage and recovery system according to one embodiment of the invention.

DETAILED DESCRIPTION OF THE INVENTION

[0053] The present invention relates to a system for the exchange of heat between a fluid and heat storage particles. The heat exchange system comprises at least one heat exchange zone, in which the fluid and a fluidized bed flow. The fluidized bed comprises heat storage particles. According to the invention, the heat exchange system comprises fluid circulation apparatus configured to cause the fluid to circulate as a crossflow with respect to the fluidized bed, in the heat exchange zone, and to cause the fluid to circulate from the outlet toward the inlet of the fluidized bed in the heat exchange zone. To simplify, in the remainder of the description, the circulation of the fluid from the outlet toward the inlet of the fluidized bed in the heat exchange zone is considered to be a circulation referred to as countercurrent because, on the whole, the fluid follows a path that leads in the opposite direction to the fluidized bed. However, unlike conventional countercurrent flows, the fluid and the fluidized bed do not have paths in opposing directions that are parallel. The countercurrent and crossflow circulation of the fluid and of the fluidized bed makes it possible for the exchange of heat to achieve a high efficiency. Thus it is possible to optimize the heat stored in the heat storage particles.

[0054] The heat storage particles are small sized which are elements (for example measuring between 0.02 and 1 mm) able to store heat.

[0055] A fluidized bed is made up of a solid phase composed of small sized particles and of a flowing fluid phase. For example, the fluid phase may be gaseous, in the form of air or a rare gas. The fluid phase may be injected at one end

of the heat exchange zone, near the inlet (injection) of the particles to form the fluidized bed.

[0056] The circulation is described as countercurrent because the fluid enters the heat exchange zone on the outlet side of the fluidized bed, and the fluid leaves the heat exchange means on the inlet side of the fluidized bed. According to one feature of the invention, the fluidized bed may have a downward path and the fluid may have an upward path. Alternatively, the fluidized bed may have an upward path and the fluid may have a downward path.

[0057] The flow is described as crossflow because the direction in which the fluid flows is not parallel to the flow of the fluidized bed in that the fluid crosses the fluidized bed. According to one embodiment of the invention, the fluid flows in a direction substantially perpendicular, for example between 60 and 120° (preferably between 75 and 105° to the direction of flow of the fluidized bed.

[0058] According to an alternative form of embodiment of the invention, the heat exchange system according to the invention may comprise solid particles or particles in the form of capsules containing a phase change material (PCM). These materials also make it possible to reduce the volume of the potential storage means because they allow a large quantity of energy to be stored in the form of latent heat. A compromise between efficiency and cost may also be reached by combining PCMs with storage materials, using sensible heat to store the heat, in the fluidized bed. Phase change materials that can be used include the following materials: paraffins with a melting point of below 130° C., salts which melt at temperatures above 300° C., mixtures (eutectics) which make it possible to have a broad range of melting points.

[0059] The solid particles (irrespective as to whether or not they are phase change materials) may have any of the known shapes employed in conventional granular environments (beads, cylinders, extrusions, trilobe particles, etc.) and any other shape that makes it possible to maximize the surface area for exchange with the gas. For preference, the particles are in the form of beads, so as to limit problems with attrition. The particle size may vary between 0.02 mm and 1 mm, preferably between 0.05 and 0.5 mm and more preferably still, between 0.07 and 0.2 mm.

[0060] According to an alternative form of embodiment of the invention, the fluid may be a gas and notably air. The fluid may be a gas that is to be cooled or heated by the particles in the heat exchange zone.

[0061] According to one embodiment of the invention, the fluid circulation apparatus may comprise one or more means of injecting for withdrawing the fluid in the exchange zone. The injection and withdrawing means are able to cause the fluid to circulate in a direction substantially perpendicular to the circulation of the fluidized bed.

[0062] When the fluid circulation apparatus comprises a plurality of injectors and withdrawing means, these may be spread along the entire length of the exchange zone. Preferably in this case, the injectors and withdrawing means may be combined in such a way that the fluid circulates through all the injection and withdrawing means consecutively. Thus, it is possible to encourage exchanges of heat by means of several consecutive passes of the fluid through the fluidized bed.

[0063] Advantageously, the injectors of the fluid are situated in the lower part of the exchange zone and the means for withdrawing the fluid are situated in the upper part of the

exchange zone. Thus, the fluid enters the lower part of the exchange zone, passes through the exchange zone, crosses the fluidized bed, then re-emerges in the upper part of the exchange zone. In addition, the fluid that enters the withdrawing means can be fed back to the adjacent injector by means external to the exchange zone. The adjacent injector, to which the fluid is reconveyed, are the injectors situated upstream from the previous injector in the direction of circulation of the fluidized bed.

[0064] According to one embodiment of the invention, the heat exchange zone is formed by a pipe, a duct, a column or any similar device. The pipe (or duct) may be of circular, rectangular, elliptical, etc. cross section.

[0065] According to an alternative form of embodiment of the invention, the flow of the fluidized bed may be achieved under gravity. Thus, the energy required to allow the fluidized bed to flow is lower. In this case, the heat exchange zone may be inclined with respect to the horizontal. For preference, the angle of inclination of the exchange zone with respect to the horizontal is between 5 and 60°.

[0066] According to an alternative embodiment of the invention, several heat exchange zones are positioned in parallel. Thus it is possible to limit the length of the heat exchange zones while at the same time encouraging the exchange of heat.

[0067] FIGS. 1a and 1b illustrate a heat exchange system 1 according to one embodiment of the invention to which the invention is not limited. FIG. 1a is a longitudinal view of the heat exchange system 1, and FIG. 1b is a cross section of the heat exchange system. The heat exchange system 1 comprises a pipe of rectangular cross section which is also inclined with respect to the horizontal. The internal volume of the pipe forms a heat exchange zone 2. Within the heat exchange zone 2, a fluidized bed LP, comprising particles 3, circulates under gravity from the inlet 4, situated at the higher end of the pipe, toward the outlet 5, situated toward the lower end of the pipe. The fluid F circulates on the whole upward from the inlet 15 toward the outlet 16. Thus the fluid flows countercurrentwise with respect to the fluidized bed. In addition, the heat exchange system comprises a plurality of injection 6 and withdrawal means 6 which are configured to cause the fluid F to circulate in an inclined direction, which is substantially perpendicular, with respect to the circulation of the fluidized bed LP. The fluid crosses the fluidized bed and, while seeking the path of least resistance and re-emerges via the nearest withdrawal point in the upper section of the pipe. It is then reconveyed, in means external to the pipe, toward the lower part of the pipe where it is reinjected into the heat exchange zone 2 by the adjacent means of injection 6 situated upstream of the previous means of injection in the direction of circulation of the fluidized bed. Thus, in one pass, the fluid flows as a crossflow with respect to the fluidized bed with the overall flow throughout the pipe being countercurrentwise. In this figure, the means that fluidized the particles in order to form the fluidized bed have not been illustrated.

[0068] FIG. 2 schematically illustrates the thermal profile T along the heat exchange zone for a heat exchange system according to the embodiment of FIGS. 1a and 1b. In this figure, T_F corresponds to the temperature of the fluid, and T_{LP} corresponds to the temperature of the fluidized bed within the heat exchange zone. It should be noted that the thermal profile is close to that of a countercurrent heat

exchanger. Thus, the maximum of energy is recuperated by the particles, thus reducing the temperature to approach a concurrent exchange.

[0069] According to one embodiment of the invention (which is compatible with all the alternative forms and all the combinations of alternative forms described herein-above), the heat exchange system may further comprise at least one storage reservoir for storing the heat storage particles. In this case, the heat exchange zone may be situated between two reservoirs. According to one embodiment of this configuration, one of the reservoirs may contain hot particles and another of the reservoirs may contain cold particles. Thanks to these reservoirs it is therefore possible to store the heat exchanged between the fluid and the particles. Between two reservoirs, there may be several heat exchange zones provided in parallel. The fact that the heat exchange does not take place within the reservoirs means that it is possible to have a volume in which the particles are stored at a uniform temperature, something which is important to the efficiency of the system. Specifically, within the reservoir, all of the particles have substantially constant temperature.

[0070] According to one design of this embodiment, the heat exchange system may comprise three reservoirs and at least two heat exchange zones. For this configuration, a first exchange zone may be provided between a first reservoir and a second reservoir, and a second exchange zone may be provided between the second reservoir and a third reservoir.

[0071] For example, the first and third reservoirs may store cold particles and the second reservoir may store hot particles. Thus, in the first exchange zone the fluid is cooled and in the second exchange zone the fluid is heated.

[0072] Alternatively, the first and third reservoirs may store hot particles and the second reservoir may store cold particles. Thus, in the first exchange zone, the fluid is heated, and in the second exchange zone the fluid is cooled.

[0073] According to an alternative form of this configuration, the heat exchange system may comprise means for transporting the particles from the third reservoir to the first reservoir. These transport means may be pneumatic, may comprise an endless screw system, etc.

[0074] The key advantages of the heat exchange and storage system according to this embodiment are:

[0075] the exchanges of heat between the heat-transfer fluid and the particles are maximized, and the size of the system is reduced accordingly, thanks to two factors:

[0076] the exchanges take place under conditions in which the solid is fluidized.

[0077] the thermal profile established in the heat exchange zone is close to that of a countercurrent exchanger.

[0078] the hot and cold temperatures of the system are kept constant. Specifically, the hot and cold particles are stored at uniform temperature in insulated volumes, thereby making it possible to get around the problem of maintaining the thermocline in the reservoir, as is the case with fixed-bed heat storage systems (where the hot point and the cold point are within one and the same reactor).

[0079] with respect to a fixed-bed storage system, there are no risks associated with poor distribution of the solid.

[0080] the system allows for flexibility because partial charging and discharging are facilitated. Specifically, it is possible at any time to cut off the supply of solid to the heat exchange zone and to heat/cool only part thereof.

[0081] FIG. 3 illustrates a heat exchange system according to one embodiment of the invention to which the invention is not limited. In this figure, the circulation of the heat storage particles is depicted as white arrows, the circulation of the fluid is depicted as grey arrows, and the circulation of the fluidization fluid is depicted by a shaded arrow. The heat exchange system comprises a first storage reservoir 7 for storing the heat storage particles. The particles from the first reservoir 7 are discharged into a first exchange zone 2 and are fluidized by fluidizing means 11. The exchange zone 2 comprises at least one inclined pipe which may be as per the exchange zone in FIG. 1a. The fluid flows countercurrentwise and as a crossflow in the first heat exchange zone 2 with respect to the flow of the fluidized bed. On leaving the first exchange zone 2, the particles are stored in the second reservoir 8. The particles from the second reservoir 8 are discharged into a second exchange zone 2 and are fluidized by fluidizing means 11. The second exchange zone 2 comprises at least one inclined pipe and may be as per the exchange zone in FIG. 1a. The fluid circulates countercurrentwise and as a crossflow in the second heat exchange zone 2 with respect to the flow of the fluidized bed. On leaving the second exchange zone 2, the particles are stored in the third reservoir 9. The particles from the third reservoir 9 are transported by transport means 10 to the first reservoir 7. The first and third reservoirs 7 and 9 may be cold-particle reservoirs and the second reservoir 8 may be a reservoir of hot particles. In this case, the first exchange zone 2 allows cooling of the fluid and the second exchange zone 2 allows the heating of the fluid.

[0082] Furthermore, the present invention relates to a compressed gas energy storage and recovery system equipped with a heat storage means (for example of the AACAES type). In this embodiment, the pressurized gas (often air) is stored cold. The energy storage and recuperation system according to the invention comprises:

[0083] at least one gas compression means (or compressor), and preferably several staged gas compression means. The gas compression means may be driven by a motor, notably an electric motor;

[0084] at least one means (also referred to as reservoir) for storing the gas compressed by the gas compression means. The compressed gas storage means may be a natural reservoir (for example an underground cavity) or otherwise. The compressed gas storage means may be at the surface or beneath the ground. In addition, it may be formed of a single volume or of a plurality of volumes which may or may not be interconnected;

[0085] at least one means of expanding the gas (also referred to as an expander or turbine), allowing the compressed and stored gas to be expanded, and preferably several staged gas expansion means. The gas expansion means allows energy, notably electrical energy, to be generated, by means of a generator;

[0086] at least one heat exchange system allowing storage of the heat derived from the gas compressed during the energy storage phase and allowing the stored heat to be restored to the compressed gas during the energy restitution phase with the heat exchange system pref-

erably being positioned at the outlet of the compression means and at the inlet of the expansion means. According to the invention, the heat exchange system comprises solid heat storage particles. These solid particles exchange heat with the gas during the energy storage and restitution phases with the heat being stored in the particles between these two phases. According to the invention, the heat storage systems are one of the alternative forms of embodiments described hereinabove, or as per one of the combinations of the alternative forms described hereinabove.

[0087] The terms “staged compression means” (and, respectively, “staged expansion means”) are used when a plurality of compression (or respectively expansion) means are mounted in succession one after the other in series. The compressed (or respectively expanded) gas leaving the first compressor (or respectively expander) and then passes to a second compressor (or respectively expander), and so on. A compressor or an expander of the plurality of staged compressors or expanders is then referred to as a compression or expansion stage. Advantageously, when the system comprises a plurality of compression and/or expansion stages, a heat exchange system is placed between each compression and/or expansion stage. Thus, the compressed gas is cooled between each compression, making it possible to optimize the efficiency of the next compression, and the expanded gas is heated between each expansion, making it possible to optimize the efficiency of the next expansion. The number of compression stages and the number of expansion stages may be between 2 and 10 and preferably between 3 and 5. Preferably, the number of compression stages is the same as the number of expansion stages. Alternatively, the compressed gas energy storage and recovery system (for example of AACAES type) according to the invention may contain a single compression means and a single expansion means.

[0088] According to an alternative form of embodiment of the invention, the compressors, staged or otherwise, may be reversible, so that they can operate both for compression and for expansion. Thus, it is possible to limit the number of devices employed in the system according to the invention, allowing a saving in terms of weight and volume in the system according to the invention.

[0089] According to an alternative form of embodiment, the heat exchange systems used between the compression stages may be those used between the expansion stages.

[0090] The system according to the invention is suited to any type of gas, notably to air. In this case, the inlet air used for compression may be taken from the ambient environment, and the air leaving after expansion may be released into the ambient environment. In the remainder of the description, only the alternative form of embodiment using compressed air, and its AACAES application, will be described. However, the system and the method are valid for any other gas.

[0091] FIG. 4 illustrates one nonlimiting exemplary embodiment of an AACAES system according to the invention. In this figure, arrows drawn in solid line illustrate the circulation of the gas during the compression steps (energy storage steps) and arrows drawn in dotted line illustrate the circulation of the gas during the expansion steps (energy restoration steps). This figure illustrates an AACAES system comprising a single compression stage 12, a single expansion stage 14 and a heat exchange system 1. The system

comprises a storage reservoir 13 for storing the compressed gas. The heat exchange system 1 is interposed between the compression/expansion stage 12 or 14 and the storage reservoir 13 for storing the compressed gas. Conventionally, during the energy storage (compression) phase, the air is first of all compressed in the compressor 12 then cooled in the heat storage system 1. The compressed and cooled gas is stored in the reservoir 13. The heat storage particles of the heat storage system 1 are hot following the cooling of the compressed gas in the compression phase. During energy recovery (expansion), the stored compressed gas is heated in the heat storage system 1. Next, in the conventional way, the gas passes through one or more expansion stages 14 (one stage according to the example illustrated in FIG. 1).

[0092] The compressed gas energy storage and recovery system according to the invention is not limited to the example of FIG. 4. Other configurations may be envisioned: a different number of compression and/or expansion stages, the use of reversible device providing both compression and the expansion, etc.

[0093] The heat exchange system according to the invention comprising at least one reservoir and at least one heat exchange zone is particularly well suited to the compressed gas energy storage and recovery system, particularly the embodiment illustrated in FIG. 3. Specifically, one reservoir allows the storage of the particles which are hot following the exchange of heat in the exchange zone during the energy storage phase and allows the hot particles to be released for the exchange of heat in the exchange zone for the energy recovery phase.

[0094] Alternatively, the heat exchange system according to the invention may be used for any type of use that requires the storage of heat, notably for the storage of solar or wind energy or for any type of industry including metallurgy, etc.

[0095] Furthermore, the present invention relates to a method for the exchange of heat between a fluid and heat storage particles. This method may perform the following steps:

[0096] a) a fluidized bed comprising heat storage particles is circulated in a heat exchange zone; and

[0097] b) the fluid is circulated in the heat exchange zone as a crossflow with respect to the fluidized bed, from the outlet toward the inlet of the fluidized bed in the heat exchange zone (namely in a direction that is on the whole countercurrentwise with respect to the fluidized bed).

[0098] The crossflow circulation generally in the opposite direction (the fluid flowing from the outlet toward the inlet of the fluidized bed in the heat exchange zone) makes it possible to achieve high efficiency of the heat exchange.

[0099] The heat exchange method can be performed by means of the heat exchange system according to the invention.

[0100] The fluid may be a gas, notably air.

[0101] According to one implementation of the invention, the fluid may be made to circulate in the heat exchange zone in several consecutive passes, each pass being performed in a portion of the heat exchange zone. This implementation may be in accordance with the operation of the system illustrated in FIGS. 1a and 1b.

[0102] According to one embodiment of the invention, the fluidized bed may be made to circulate in a downward path and the fluid in an upward path. For preference, the fluidized bed may be made to circulate in the heat exchange zone

under gravity, preferably by use of a heat exchange zone that is inclined with respect to the horizontal.

[0103] According to one embodiment, the heat storage particles may be stored in a first reservoir prior to the exchange of heat and the heat storage particles may be stored after the step of heat exchange. Thus, it is possible to store the heat exchanged.

[0104] According to one configuration of this embodiment, the following steps may be implemented:

[0105] a) storing the particles in a first reservoir;

[0106] b) exchanging heat between a fluidized bed comprising the particles stored in the first reservoir and a fluid;

[0107] c) storing the particles leaving the heat exchange in a second reservoir;

[0108] d) performing the exchange of heat between a fluidized bed comprising the particles stored in the second reservoir and a fluid; and

[0109] e) storing the particles leaving the heat exchange in the first reservoir or in a third reservoir.

[0110] In instances in which the particles are stored in a third reservoir, the method may comprise an additional step of transporting the particles from the third reservoir to the second reservoir.

[0111] The present invention also relates to a compressed gas storage and recovery method in which the following steps are performed:

[0112] a) compressing a gas, notably by a compressor;

[0113] b) cooling the compressed gas by an exchange of heat in a heat exchange system according to the invention;

[0114] c) storing the cooled compressed gas, notably by a compressed gas storage;

[0115] d) heating the stored compressed gas by exchange of heat in the heat exchange system according to the invention; and

[0116] e) expanding the heated compressed gas in order to generate energy, for example by a turbine in order to generate electrical energy.

[0117] According to the invention, the exchange of heat between the gas and the particles is performed in a heat exchange zone with the fluid flowing countercurrentwise and as a crossflow with respect to the fluidized bed that comprises the particles. Thus, the energy storage and restoration of the AACAES type method are optimized.

[0118] According to one aspect of the invention, the method comprises several successive compression steps, using compressors placed in series, also referred to as staged compressions. In this case, steps a) and b) are repeated for each compression stage. Thus the gas is compressed and cooled several times.

[0119] According to one feature of the invention, the method comprises several successive expansion steps, using expanders placed in series, also referred to as staged expansions. In this case, steps d) and e) are repeated for each expansion stage. Thus the gas is heated and expanded several times.

[0120] Step a) involves compressing a gas, for example air. This may notably be air taken from the ambient environment.

[0121] Step b) allows the compressed gas to be cooled after each compression step, making it possible to optimize the efficiency of the next compression and/or the storage of energy. The heat storage means make it possible, when

storing the compressed gas (compression) to recuperate the maximum amount of heat originating from the compression of the gas at the outlet of the compressors and to reduce the temperature of the gas before it passes on to the next compression or before storage. For example, the compressed gas may pass from a temperature higher than 150° C., for example approximately 190° C. to a temperature of below 80° C., for example of around 50° C.

[0122] Step c) may be performed within a compressed gas storage means which may be a natural reservoir (for example an underground cavity) or otherwise. The compressed gas storage means may be at the surface or below the ground. In addition, it may be formed of a single volume or of a plurality of volumes that may or may not be interconnected. During storage, the compressed gas storage means is closed.

[0123] The compressed gas is stored until such time as the stored energy is to be recuperated. Step d) and following are performed at the time at which the stored energy is to be recuperated.

[0124] Step d) allows the compressed air to be heated before each expansion, thereby making it possible to optimize the efficiency of the next expansion. For step d) it is possible to use the heat storage particles that were used for cooling during step b). The heat storage means make it possible, when restoring energy, to restore a maximum amount of stored heat by increasing the temperature of the gas before it passes on to the next expansion. For example, the gas may pass from a temperature of below 80° C., for example of around 50° C., to a temperature higher than 150° C., for example of around 180° C.

[0125] During step e), the compressed gas is expanded. Expanding the compressed gas makes it possible to generate energy. This expansion may be performed by a turbine which generates electrical energy. If the gas is air, the expanded air may be discharged into the surrounding environment.

[0126] The compressed gas energy storage and recovery system according to the invention can be used for storing intermittent energy, such as wind or solar energy so that this energy can be used when desired.

1-20. (canceled)

21. A heat exchange system for exchange of heat between a fluid and heat storage particles comprising at least one heat exchange zone in which the fluid and a fluidized bed including the heat storage particles flows, means for circulating the fluid which is configured to provide a cross-flow circulation of the fluid with respect to the fluidized bed in the heat exchange zone which causes the fluid to circulate from an outlet toward an inlet of the fluidized bed in the at least one heat exchange zone.

22. The system as claimed in claim 21, wherein the means of circulating the fluid comprises means of injecting and means of withdrawing the fluid which causes the fluid to circulate in a direction transverse to circulation of the fluidized bed.

23. The system as claimed in claim 22, wherein the means for circulating comprises a plurality of means for injecting and means for withdrawing the fluid which are combined to cause the fluid to circulate through each means for injecting and each means for withdrawing consecutively, the means of injecting and the means of withdrawing being disposed consecutively along the heat exchange zone, the fluid flowing from a means for withdrawing being introduced into the

exchange zone by a means of injecting located upstream relative to circulation in the fluidized bed.

24. The system as claimed in claim **21**, wherein the at least one heat exchange zone comprises a pipe.

25. The system as claimed in claim **22**, wherein the at least one heat exchange zone comprises a pipe.

26. The system as claimed in claim **23**, wherein the at least one heat exchange zone comprises a pipe.

27. The system as claimed in claim **21**, wherein gravitation contributes to the fluid flow in the heat exchange zone.

28. The system as claimed in claim **22**, wherein gravitation contributes to the fluid flow in the heat exchange zone.

29. The system as claimed in claim **23**, wherein gravitation contributes to the fluid flow in the heat exchange zone.

30. The system as claimed in claim **24**, wherein gravitation contributes to the fluid flow in the heat exchange zone.

31. The system as claimed in claim **27**, wherein the heat exchange zone is inclined relative to a horizontal orientation.

32. The system as claimed in claim **21**, wherein the particles comprise phase change materials.

33. The system as claimed in claim **21**, wherein the fluid circulates in an upward direction.

34. The system as claimed in claim **21**, wherein the fluid is a gas.

35. The system as claimed in claim **34**, wherein the fluid comprised air.

36. The system as claimed in claim **21**, comprising at least two storage reservoirs for storing the heat storage particles with the at least one heat exchange zone being located between the reservoirs.

37. The system as claimed in claim **36**, comprising a first storage reservoir for storing the particles, a second storage reservoir for storing the particles, at least one first heat exchange zone disposed between the first and second reservoirs and a third storage reservoir for storing the particles, and at least one second heat exchange zone disposed between the second and the third reservoirs.

38. The system as claimed in claim **37**, comprising means for transporting the heat storage particles from the third reservoir to the first reservoir.

39. A compressed gas energy storage and recovery system, in accordance with claim **21**, comprising at least one gas compressor at least one compressed gas storage, and at least one expander for expanding the compressed gas to generate energy, wherein the compressed gas energy storage and recovery system comprises at least one heat exchange system.

40. A method for exchanging heat between a fluid and heat storage particles, comprising:

- a) a fluidized bed including the heat storage particles circulated in a heat exchange zone; and

- b) the fluid is circulated in the heat exchange zone as a crossflow with respect to the fluidized bed from an outlet toward an inlet of the fluidized bed in the heat exchange zone.

41. The method as claimed in claim **40**, comprising using gravity to contribute to circulation of the fluid in the heat exchange zone.

42. The method as claimed in claim **40**, wherein the fluid is circulated in a direction transverse to a direction of circulation of the heat storage particles in the fluidized bed.

43. The method as claimed in claim **41**, wherein the fluid is circulated in a direction transverse to a direction of circulation of the heat storage particles in the fluidized bed.

44. The method as claimed in claim **40**, wherein the heat storage particles are stored in a first reservoir prior to the heat exchange and the heat storage particles are stored in a second reservoir after heat exchange in the heat exchange zone.

45. The method as claimed in claim **41**, wherein the heat storage particles are stored in a first reservoir prior to the heat exchange and the heat storage particles are stored in a second reservoir after heat exchange in the heat exchange zone.

46. The method as claimed in claim **42**, wherein the heat storage particles are stored in a first reservoir prior to the heat exchange and the heat storage particles are stored in a second reservoir after heat exchange in the heat exchange zone.

47. The method as claimed in claim **44**, comprising:

- a) storing the heat storage particles in the first reservoir;
- b) exchanging heat is between the heat storage particles stored in the first reservoir and fluid;
- c) storing the heat storage particles leaving the heat exchange in the second reservoir;
- d) exchanging heat between the particles stored in the second reservoir and the fluid; and
- e) storing the particles leaving the heat exchange in the first reservoir or in a third reservoir.

48. The method as claimed in claim **47**, comprising transporting the heat storage particles from the third reservoir to the first reservoir.

49. A compressed gas energy storage and recovery method in accordance with claim **21** comprising:

- a) compressing a gas;
- b) cooling the compressed gas by exchange of heat in the heat exchange system;
- c) storing the cooled gas;
- d) heating the cooled compressed gas by recovery of heat from the heat exchange system; and
- e) expanding the heated compressed gas to generate energy.

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