

A system for storing and transferring heat, comprising a solid bulk materialField of invention

The present invention relates to a system for storing and transferring heat in a high-temperature heat storage system, wherein the thermal energy is stored in a solid bulk material.

Prior art

The international patent application WO 2020183063 A1 describes a system and corresponding method for storing and transferring heat (the reference signs herein relating to WO 2020183063 A1). Said system (100, 300, 400) comprises at least one resistor (101, 301, 401) for generating thermal energy from electrical energy; at least one heat storage (102, 302, 402) with a solid material (e.g. sand, aggregate, gravel) for storing the generated thermal energy, preferably arranged underground and for storing energy up to 1200 °C; a heat transfer mechanism (103, 303, 403) for transferring heat from the heat storage (102, 302, 402) to a heat consumption system (104, 304, 404) for further use. The resistor (101) may be arranged within or outside the heat storage (102). The heat transfer mechanism (103, 303, 403) is either a closed gas circuit (first embodiment of the prior art) or a thermosiphon system with a plurality of tubes closed at both ends (second embodiment of the prior art). The heat storage (102, 302, 402) comprises (e.g. stainless steel) tubes arranged in a solid material for transporting the gas.

In the first embodiment, the closed gas circuit transfers heat to and from the heat storage (102, 302, 402), e.g. using nitrogen at a pressure of 1 to 50 bar and preferably using a bi-directional fan. In this embodiment, the gas is routed through the tubes in the heat storage (102, 302, 402). In the second embodiment, the thermosiphon system may comprise thermosiphon tubes filled with liquid up to a maximum of 25 % of their volume, e.g. vertically arranged stainless steel thermosiphon tubes filled at the bottom with water, which after heating may completely turn into steam, or even supercritical steam, rising to the top of the tube. Optionally, said system comprises a secondary heat transfer circuit (312, 412) and/or a secondary heat storage (313, 413). Optionally, said system comprises a power generator for generating power from fluctuating sources or overcapacity of the

electrical grid, such as a solar panel, wind turbine, tidal power plant, or overloaded electrical grid. The heat storage (102, 302, 402) may be enclosed with an insulating layer with a low thermal conductivity material, such as an artificial aggregate having a thermal conductivity below 0.3 W/mK.

- 5 The disadvantage of the above system with the closed gas circuit inside the storage space, as the heat transfer mechanism, is the necessity to provide a heat transfer surface for the gaseous medium by means of additional elements - tubes. The heat transfer surface, and thus the number of elements inserted, is proportional to the required power and stored energy and constitutes a significant part of the mass of the heat accumulator.
- 10 The heat conduction between the heat storage material and the tube wall requires a thermal gradient which increases the temperature difference between the inlet and outlet temperature, thereby reducing the efficiency of the thermal energy storage. The additional elements for the conduction of the medium must withstand the maximum temperature in the accumulator, and possibly additionally the internal pressure of the medium. The high
- 15 heat resistant metal materials used for these elements have a high cost, which significantly increases the cost of the accumulator in relation to the stored energy. Even with durable metal materials, the mechanical properties decrease significantly with increasing temperatures and often do not reach the thermal resistance of conventional refractory materials. The use of metal materials in the high temperature range thus has
- 20 its limits, limiting both the operating temperature and the storage capacity. Due to the cost of the tubes, their cross-sectional area has to be minimised, leading to high flow velocities and thus a limited possibility of temperature stratification in the storage. A system using heat from the storage medium must then accept a large range of outlet temperatures of the medium.
- 25 The disadvantage of the above system having the thermosiphon system, as the heat transfer mechanism, is the dependence on the physical parameters of the medium, the mutual relationship between pressure and temperature in the heat exchanging circuit, while at high temperatures it is necessary to operate the heat exchanging circuit at high pressures. The unidirectional flow of energy in a closed tube, from the lower end to the
- 30 upper end, does not allow temperature stratification of the energy storage. In addition, this system has the disadvantages of the closed gas circuit system described above.

Similar tube-comprising systems are known from the Chinese patent application CN 108007246 A (thermal energy is stored in a molten salt), the Japanese patent application

JP H102616 A (thermal energy is stored in a metal block), and the US patent application US 2012111006 A1 (thermal energy is stored in a bulk material in a structural labyrinth of the storage space).

Therefore, in the prior art, there is a need to provide a system and a corresponding
5 method for storing and transferring heat with a higher thermal energy storage efficiency, characterized by the necessary thermal resistance, lower operating pressure, the possibility of thermal stratification of the thermal energy storage and lower input costs in relation to the stored thermal energy.

Summary of the invention

10 It is an object of the invention to provide a heat storage and transfer system that uses non-metal materials for distributing a heat transfer medium in a heat storage, and that provides for the recovery of heat loss passing through a thermally insulating heat storage shell. At the same time, this system allows a high degree of stratification of the heat storage, thereby allowing the recovery of the stored thermal energy at sustained high
15 temperatures, which differ minimally from the inlet temperature. The blower system (see details below) allows precise control of the outlet temperature and power.

The above features are intended to improve the economic and technical parameters of the high-temperature thermal energy storage. The increase in maximum operating temperature and the continuous output of thermal energy at high temperatures will enable
20 the use of heat storage technology in applications not yet exploited. High temperatures also typically increase the efficiency of technological processes and other energy transformations.

It is also an object of the invention to provide a method of storing and transferring heat using the system described herein.

25 The above objective is achieved by a heat storage and transfer system comprising

- a. at least one heat source for generating thermal energy;
- b. a high-temperature heat storage with a bulk refractory material filling a high-temperature storage space for storing the generated thermal energy;
- c. at least one heat consumption system for using the stored thermal energy; and

- d. a heat transfer mechanism for transferring heat from the heat source to the high-temperature heat storage system and from the high-temperature heat storage system to the heat consumption system, wherein the heat transfer mechanism is a closed gas circuit connecting the heat source, the high-temperature heat storage system and the heat consumption system, wherein the high-temperature heat storage system is partially enclosed by a load-bearing inner shell.

The underlying idea of the system is that the bulk refractory material comprises a particle fraction having a sphericity in the range of 0.4 to 1 and a mean particle size in the range of 0.5 to 20 mm, wherein the ratio of the volume of the largest to the smallest particles is at most 5:1. This particle fraction ensures the permeation of both hot and cooled gas without the need for gas conducting tubes in the bulk refractory material. The maximum ratio of 5:1 indicates the maximum uniformity in particle size, thus ensuring the greatest spacing, and uniformity of particle temperature changes in the flowing gas, thereby minimizing the extent of the steep thermal gradient region. Requiring a uniform, overly narrow aggregate fraction is more technically challenging than higher particle size tolerances. A particle size tolerance greater than 5:1 will already have a significant effect on aggregate spacing and heating uniformity, while having a minimal effect on the technical complexity of aggregate preparation (and hence cost). A ratio higher than 5:1 would result in a fraction containing particles of excessively different sizes, thereby reducing the mean size of the gaps between the particles.

The load-bearing inner shell is further enclosed with a thermal-insulating outer shell such that a gas gap is arranged between the load-bearing inner shell and the thermal-insulating outer shell for recovering heat loss from the high-temperature heat storage, penetrating through the load-bearing inner shell. This gas gap, together with an interconnecting gas channel, connects the high-temperature heat storage to at least one technological area which is further connected to at least one heat consumption system. The hot gas channel further connects the high-temperature heat storage to at least one heat source.

The load-bearing inner shell may comprise high-temperature thermal insulation on the side adjacent to the high-temperature storage space to prevent heat transfer from the high-temperature heat storage space to the load-bearing inner shell more effectively.

In one embodiment of the present invention, the heat source may be an inlet heat exchanger. A blower system may be arranged in the technological area for conducting cooled gas from the high-temperature storage space through the gas gap, the interconnecting gas channel, the technological area and a first outlet gas channel to at least one inlet heat exchanger. At least one hot gas channel may be arranged for conducting hot gas from the inlet heat exchanger to the gas layer above the high-temperature storage space.

Alternatively or in addition to the embodiment above, the heat source may be at least one electrically heated element. A blower system may be arranged in the technological area for conducting cooled gas from the high-temperature storage space through the gas gap, the interconnecting gas channel and the technological area to a second interconnecting gas channel and the hot gas channel, and further in thermal contact with the electrically heated element for heating the gas to the gas layer above the high-temperature storage space. The electrically heated element may be arranged inside the load-bearing inner shell outside the high-temperature storage space, preferably in the hot gas channel.

In addition to the embodiments above, the heat transfer system may be an outlet heat exchanger. A blower system may be arranged in the technological area for conducting cooled gas from the outlet heat exchanger through a second gas inlet channel, the technological area, the interconnecting gas channel and the gas gap to the high-temperature storage space. At least one hot gas channel may be arranged for conducting hot gas from the high-temperature storage space from the gas layer above the high-temperature storage space to at least one outlet heat exchanger.

The first inlet gas channel and the first outlet gas channel may be arranged coaxially with each other such that the first outlet gas channel surrounds the first inlet gas channel. Similarly, the second inlet gas channel and the second outlet gas channel may be arranged coaxially with each other such that the second inlet gas channel surrounds the second outlet gas channel. Similarly, the interconnecting gas channel and the hot gas channel may be arranged coaxially with each other such that the interconnecting gas channel surrounds the hot gas channel. The coaxial arrangement prevents the heat from the hot gas from transferring to the surroundings and allows heat recovery in the cooled gas.

The gas gap can be connected via an air channel with a two-way valve, which is further connected to the surroundings via a safety inlet gas channel and a safety outlet gas channel. This ensures operational safety and the possibility of pressure equalization.

5 The bulk refractory material may be any one from the group comprising basalt, andesite, dacite, artificial sintered aggregate, ceramic material, blast furnace slag, compressed graphite with glassy carbon on the surface, carbide and nitride.

10 A temperature sensor may be arranged in the first gas inlet channel, in the first gas outlet channel, in the second gas inlet channel, in the second gas outlet channel, in the space of the cooled gas inlet-outlet, in the space where an enclosure of the electrically heated element connects to the gas layer above the high-temperature storage space, and in the space of the hot gas channel upstream of the inlet to the enclosure, wherein each temperature sensor is connected to a control unit.

15 A maintenance area may be arranged under the high-temperature storage space for housing a collection and transport system for separated dust and/or for housing a collection and transport system for material to be reprocessed.

At least one distribution valve may be provided in the hot gas layer above the high-temperature storage space for the inlet of the bulk refractory material at operating temperatures of the high-temperature heat storage space.

20 The mean particle size may be in the range of 0.5 mm to 20 mm, preferably 0.5 mm to 10 mm, wherein the ratio of the mean particle size of the bulk refractory material to the total height of the high-temperature storage space may be in the range of 1:1500 to 1:6000.

25 The above objective is further achieved by a method of storing and transferring heat using the system for storing and transferring heat described herein. The method comprises the following steps of heat storage:

- a. generating thermal energy in at least one heat source to form hot gas;
- b. transferring the hot gas from the heat source to the high-temperature heat storage by means of a closed gas circuit as a heat transfer mechanism;

- c. storing the generated thermal energy from the hot gas in the high-temperature heat storage with a bulk refractory material comprised in the high-temperature storage space to form a cooled gas;
- d. transferring the cooled gas from the high-temperature heat storage to the heat source by means of the closed gas circuit as the heat transfer mechanism; and
- e. optionally repeating steps a. to d.;

and then the following steps of stored heat consumption:

- f. transferring the cooled gas from the heat consumption system to the high-temperature heat storage by means of the closed gas circuit as the heat transfer mechanism;
- g. obtaining stored thermal energy from the high-temperature heat storage with the bulk refractory material comprised in the high-temperature storage space to form a hot gas;
- h. transferring the hot gas from the high-temperature heat storage to the heat consumption system by means of the closed gas circuit as the heat transfer mechanism; and
- i. consuming the stored thermal energy from the hot gas in at least one heat consumption system.

The underlying idea of the method is that the bulk refractory material comprises a particle fraction having a sphericity in the range of 0.4 to 1 and a mean particle size in the range of 0.5 to 20 mm, wherein the ratio of the volume of the largest to the smallest particles is at most 5:1. In steps d. and f., heat loss, escaping from the high-temperature heat storage due to heat transfer through the load-bearing inner shell surrounding the high-temperature heat storage, is recovered by conducting the cooled gas through the gas gap arranged between the load-bearing inner shell and the thermal-insulating outer shell surrounding the load-bearing inner shell.

The term 'bulk' material means 'loose' material.

The underlying idea of the invention consists in storing thermal energy directly in the bulk refractory material, without the aid of a closed tubular system inside the storage space.

By recuperating the heat loss, the dependence of the magnitude of the heat loss to the external environment on the internal temperature is substantially reduced. The economically achievable value of the maximum inner temperature is thus significantly increased.

- 5 To limit heat leakage from the high-temperature storage space, the load-bearing inner shell is provided with high-temperature thermal insulation on the inside, which can be made as a layered insulation using various refractory and high-temperature insulation materials. The optimum parameters of the high-temperature thermal insulation and the inner shell depend on optimisation calculations after specifying economic, operational
10 and physical parameters. The size and shape of the heat storage, the required time and power parameters of heat storage and extraction have a great influence.

The optimization calculation considers the difference in the heat flux intensity (T_i) passing through the high-temperature thermal insulation and the heat flux intensity (T_e) passing through the thermal-insulating outer shell, in relation to the surface heat capacity (C_{pl}) of
15 the shell. This gives the rate (R_{pl} ; in units of K.s) of heating of the shell of the high temperature storage space when the flow of cooled gas in the gas gap is stopped (stopping the extraction of heat energy from the outlet heat exchanger).

$$R_{pl} = \frac{C_{pl}}{(T_i - T_e)}$$

The basic design parameter is the time (T ; in units of s) for which no thermal energy is to
20 be removed from the storage (or the minimum thermal energy removal parameter for a certain period of time), and the temperature difference between the cooled gas (t_{chl}), which is returned to the storage after the removal of thermal energy in the outlet heat exchanger, and the maximum possible temperature in the gas gap and in the technological area (t_{max}).

$$25 \quad T = \frac{C_{pl}}{R_{pl}} \cdot (t_{max} - t_{chl})$$

The calculations show the lowest heat loss through the thermal-insulating outer shell with uniform energy extraction from the heat storage (in which the temperature in the gas gap will be maintained at a minimum level by the flow of cooled gas from the outlet heat exchanger). The temperature in the gas gap (and hence the total heat loss) will slowly
30 increase with the temperature of the load-bearing inner shell when the heat extraction

from the heat storage is interrupted. Therefore, the interruption of the heat extraction on the order of hours, the high non-uniformity of the energy supply, and the state of charge of the storage (mean temperature) do not affect the total heat loss to the external environment very much. In order to minimise the heat loss to the external environment, maximising the thermal resistance of the thermal-insulating outer shell, and the regular extraction of thermal energy is of major importance. The greater the periods of time without energy extraction that the storage facility has to sustain, the higher the required area heat capacity of the inner shell, or the thermal resistance of the thermal-insulating outer shell and the equipment of the technological area.

The main advantages of the system described herein:

- It solves the time mismatch between supply and demand of thermal and electrical energy, with lower requirements for expensive materials, more achievable lower heat losses and thus higher efficiency.
- The high temperature of the stored energy and the continuous provision of energy through the high temperature gas medium allows the technological application of heat storage where this has not been possible before.
- Due to the high temperature, it is efficient to convert (according to demand) to another form of energy, e.g. electric energy using a gas turbine or another heat engine or a thermoelectric generator.
- High temperatures, which are easier to achieve technologically, allow high energy storage densities at lower costs. For silicate refractory materials (e.g. basalt with a spacing parameter of 0.46 at a temperature difference of 800 K), the storage has a thermal capacity of 1.27 GJ/m³, corresponding to 120 to 180 kWh of electricity at 35 to 50% thermal energy conversion efficiency in the heat engine (the highest efficiency is possible with a combination of gas and steam turbine, common in steam power plants).
- The internal flow system ensures the recovery of heat energy losses passing through the thermal refractory insulation. The outer shell of the heat storage has low heat losses to the external environment, derived from the temperature of the cooled heat storage.
- No toxic or chemically reactive liquid substances are used that endanger the environment or increase operational risks.
- The storage material and the storage shell are materials already produced in large

volumes for road and building construction.

In terms of availability of large volumes and price, common bulk natural and artificial materials are suitable. Their appropriate grain size, size and gap to solid ratio, and surface density are determined by optimization calculations after specifying the economic and physical parameters of locally available materials. The size and shape of the heat storage is also a major influence. For optimal storage function, the ideal shape is a cylinder or a body with vertical or near-vertical walls with a plan section in the shape of a square, circle, ellipse or regular polyhedron (5 or more walls). In general, it is preferable to achieve the smallest possible surface-to-volume ratio, resulting in higher efficiency for larger storage volumes. The potential energy stored and recovered is directly dependent on the floor area of the storage and indirectly on the height of the storage.

The parameters of the storage will be largely determined by the physical parameters of the solid particles (bulk refractory material) filling the high-temperature storage space of the storage. Among the natural materials, microcrystalline leachable rocks with minimum alkalic content (Na_2O , K_2O) with high strength and heat resistance are suitable. These are mainly basalt, andesite and dacite. Tests verifying their resistance to thermal cycling will be necessary to assess the suitability of a particular material. For smaller storage ranges, artificial aggregates produced by sintering at high temperatures, similar to ceramics, will be particularly suitable. Blast furnace slag is also applicable.

In addition to their own mass and heat capacity, the bulk solids must have a significant proportion of gaps to allow the gas to flow around the solids to ensure favourable storage parameters. This condition is best achieved with a narrow range of solids fraction, no fines or dust fractions, and high sphericity (sphere-like shape). The roundness of the particle edges has no clear positive or negative effect on the physical parameters of the storage. Sharp or only slightly rounded edges increase the specific surface area and spacing, and thus improve the parameters, but on the other hand they lengthen and curve the gas path between the particles more, and thus have an opposing effect. From the point of view of mechanical resistance and thus particle lifetime, a higher edge roundness will be appropriate. The surface of particles with a microcrystalline structure has only a small roughness, which in most cases will affect the pressure drop only negligibly in a slow laminar flow. A large heat transfer surface area (surface area of solid particles per volume or mass - specific surface area) provides favourable parameters for heat sharing in the storage. This surface area is most dependent on the mean particle size. Small

particle size is advantageous for heat sharing but decreasing particle size causes an increase in pressure drop.

From the mathematical and physical analyses performed, it seems appropriate to maintain the ratio of the total height of the storage space to the mean particle size of the bulk refractory material in the range of 1:1500 to 1:6000. In common engineering practice, this would be a medium particle size range of 0.5 mm to 20 mm, preferably 0.5 mm to 10 mm, with a maximum particle size difference in a particular application of up to 5:1 (largest to smallest particle size). The basic parameter is the required thermal energy storage and extraction capacity based on 1 m² of floor area of the storage space. This parameter can be significantly different for storage, and for thermal energy recovery. In addition to the power of the blowers, the possible maximum thermal energy storage/retrieval capacity is mainly limited by the height of the steep thermal gradient region created by the flow of gas through the storage space. This area can be defined as an area where 90 % of the gas temperature change occurs as the gas flows through the storage space. The height of the steep thermal gradient region is a fundamental design parameter of the storage compartment. The calculation of this height is a task for the mathematical and physical analysis of gas flow through a porous medium - a layer of material particles. Other things being equal, the magnitude of this height increases as a function of the gas flow velocity and thus as a function of the power.

An example of this dependence is shown in Figure 2 - the increase in the height of the steep thermal gradient region as a function of flow velocity. The maximum extent of the steep thermal gradient region for the heat storage function is half the height of the storage space. In general, more efficient storage will be at a power/flow rate where the ratio of the height of the steep thermal gradient region to the height of the storage space is higher (e.g. 1:4, 1:5, 1:6, 1:7 or 1:8).

When an increase in the performance parameter per m² of storage area is required, the mean particle size of the bulk refractory material must be reduced to reduce the height of the steep thermal gradient region. An example of this dependence is shown in Figure 3 - reduction of the height of the steep thermal gradient region as a function of decreasing the mean particle size of the bulk refractory material.

Bidirectional gas propulsion through the storage facility will be provided by a blower system. It is advisable that the power of the blower system, compensating for the pressure

- loss, is in an economic ratio to the design heat output of the flowing gaseous medium in the heat storage. In the case where the input thermal energy is generated at least partially from electrical energy, it may be advantageous to use significantly higher flow velocities (higher blower system performance) for thermal energy storage than for reverse output
- 5 flow, since virtually all of the energy used for mechanical work in heat storage is ultimately converted to stored thermal energy. In terms of blower performance requirements, parameters of out-of-layer flow velocities in the range of 0.01 - 1 m/s (permeation of 0.01 - 1 m³ gas through an area of 1 m² /s), and pressure drops in the order of 10² to 10⁴ Pa/m of storage space height are suitable for engineering practice.
- 10 A high level of reliability of the computational mathematical-physical modelling of the heat storage space is necessary for the technical feasibility of the storage. Essential parameters specifying a specific material in the mathematical-physical model, such as pressure drop, heat transfer coefficient and heat capacity, can be verified in the laboratory on a small sample of the specific material.
- 15 The cost of energy storage materials, including the cost of processing and transport, will become more important as the size of the storage facility increases. For smaller storage sites in the order of tens of m³ of volume, bulk ceramic materials or artificially sintered aggregates with low thermal conductivity values and less emphasis on bulk weight (e.g. lightweight expanded clay granulate branded as Liapor 4-8/600) will be optimal. For large
- 20 storage sites, the thermal conductivity parameter will become less important and cheaper, non-thermally post-processed natural materials can be used with high efficiency. It is also possible to optimise the overall properties of the storage material by mixing solid particles of similar size but with different material parameters, or by depositing materially different particles in layers to promote heat stratification in the storage.
- 25 Virtually all particles, even those made of very resistant materials, will experience surface disruption and dust particle removal due to thermal cycling and the resulting volume changes. These dust particles accumulate in the channels between particles of normal size and are entrained by the gas, particularly as it flows downwards. In normal storage operation, the required peak input heat performance will be higher than the output heat
- 30 performance and thus the downward flow rate through the high-temperature storage space will be higher than the upward flow rate. Therefore, the gas will pass through a dust collector (ideally a cyclone separator equipped with a filter) after leaving the lower part of the high-temperature storage space to avoid dust fouling the channels and heat

exchangers. The heat recovery gas flow is upwards and therefore only carries exceptionally fine dust particles, without the risk of settling in the gas channel system. This flow can also recuperate the filters of the separator (preferably equipped with a vibrator).

- 5 Particle erosion, especially in durable sintered ceramic materials, is slow but permanently reduces the functional parameters of the storage. Particle erosion results in fouling and reduction of the channel cross-section between the particles. As a result, the pressure drop increases and the heat transfer coefficient decreases due to the reduction of thermal conductivity at the particle surface. The design of the storage facility must therefore
- 10 provide for the possible one-time replacement or gradual replacement of the bulk refractory material in the high-temperature storage space. For large storage tanks, it will be more practical to have gradual reprocessing and replenishment without the need to cool down the entire storage tank and thereby significantly affect operation.

An example embodiment of the present invention comprises a solution for the gradual

15 replacement of the bulk refractory material (the filling of the high-temperature storage space). The aim of the solution is to provide standard, sustainable energy storage conditions. The erosion is carried out by separating the surface parts with a size corresponding to the fineness of the material structure. In the case of natural materials, it occurs more rapidly, by separating larger dust particles and less uniformly than in the

20 case of artificial ceramic materials (finer, more uniform and more sintered structure). In general, it can be assumed that it will be possible to reprocess bulk refractory material by beating (e.g. in a drum mixer) and sieving (e.g. vibrating sieve at a slight inclination). To reduce dust and noise and to improve the quality of the process, simultaneous washing with water is advisable. Before leaving the sieve, the material is stripped of water and

25 dust on the surface by air flow. During washing, it is further dried by passing through a slowly rotating roller or by forced air passage with reduced humidity through a hopper. Unusable material of insufficient strength and size is thus separated, and the still suitable material is freed from eroded surfaces, dust and unwanted smaller particles. The result is then a reusable, desired narrow fraction of the bulk refractory material. The remainder

30 after reprocessing, the so-called "sub-sieve", can be used in another, smaller or more efficient type of storage where smaller particles are desired, or otherwise utilized. Residual dust and battered material may be further sorted and processed in the production of ceramic materials or may be used to produce new ceramic refractory

sintered particles. The energy storage technology will thus have a minimal environmental impact.

In principle, the storage can be operated at temperatures higher than those tolerated by conventional refractory silicate materials. However, this requires that all hot parts of the storage system be made of high-temperature materials with higher resistance and with inert gas as the medium. A sufficiently solid form of carbon or its compounds in the form of carbides is suitable as a storage material for maximum temperatures. Wool or foam made of carbon fibre and graphite may be used as thermal insulation material for temperatures up to 3000 °C. Heating of the storage medium to temperatures above 1200 °C can only be efficiently achieved by electrical energy, graphite resistive elements, carbon fibre resistive elements or a non-contact induction system.

Description of the drawings

Figure 1 schematically shows a high-temperature heat storage system (solid line with arrows shows hot gas, dashed line with arrows shows cooled gas, dashed line without arrows shows power lines).

Figure 2 shows an increase in the height of a steep thermal gradient region as a function of increasing flow velocity (the top of the columns shows the highest temperature and the bottom of the columns the lowest temperature).

Figure 3 shows a decrease in the height of a steep thermal gradient region as a function of decreasing mean particle size of the bulk refractory material (the top of the columns shows the highest temperature and the bottom of the columns the lowest temperature).

Figure 4 shows functional diagrams of the heat exchanging circuits (solid line with arrows shows hot gas, dashed line with arrows shows cooled gas).

Figure 5 schematically shows a distribution valve.

Examples

High-temperature heat storage design

A high-temperature heat storage arrangement where the thermal energy is bound by means of a solid bulk refractory material is shown in Figure 1. In this embodiment, the

high temperature storage comprises a thermally insulated space within a thermal-insulating outer shell 5. A predominant part of the thermally insulated space within the thermal-insulating outer shell 5 is filled by a load-bearing inner shell 3 with a high-temperature thermal insulation 2, and a high-temperature storage space 14, which is surrounded on the top and on the sides by the load-bearing inner shell 3 with the high-temperature thermal insulation 2 and on the bottom by a grid with gas channels 14.7. Between the thermal-insulating outer shell 5 and the load-bearing inner shell 3, a gas gap 4.1 is formed, and further preferably an interconnecting gas channel 4.3 or an air channel 13.3 (see more detailed description below).

The lower part of the thermally insulated space inside the thermal-insulating outer shell 5 is filled with a maintenance area 22. In the maintenance area 22, under the grid with gas channels 14.7, there is at least one hopper 21.1, at least one dust separator 20.1, and the maintenance area may also be equipped with a collection and transport system 20 for separated dust and a collection and transport system 21 for material to be reprocessed. The refractory material in the hopper 21.1 and the volume of the dust separator 20.1 is preferably insulated from the rest of the maintenance area 22 by the thermal insulation 5.2 of the maintenance area. The base structure of the high-temperature heat storage preferably comprises a base plate 3.1 resting on a load-bearing thermal insulation 5.1 (e.g. foam glass gravel) adjacent the thermal-insulating outer shell 5.

Inside the heat-insulating outer shell 5, at least one technological area 4.2 is arranged in any arrangement relative to the load-bearing inner shell 3, or in a separate space, preferably located at the height of the maintenance area and/or next to the load-bearing inner shell 3. The separated technological area 4.2 is preferably connected to the other parts of the thermally insulated space inside the thermal-insulating outer shell 5 by a coaxial heat input-output 7.3, wherein the higher temperature gas channel is inside the lower temperature gas channel.

Said higher temperature gas channel in the coaxial heat input-output 7.3 is connected to the hot gas channel 7 running through the high-temperature thermal insulation 2 and flowing into the upper part of the high-temperature storage space 14 (into the gas layer 14.6). Said lower temperature gas channel in the coaxial heat inlet-outlet 7.3 is connected to the interconnecting gas channel 4.3 running between the thermal-insulating outer shell 5 and the load-bearing inner shell 3 and flowing into the gas gap 4.1 at the cooled gas

inlet-outlet 6. The cooled gas inlet-outlet 6 is always located above the high-temperature storage space 14, close to the highest point of the gas gap 4.1. Thus, the hot gas channel 7 and the interconnecting gas channel 4.3 may preferably be arranged coaxially to the heat inlet-outlet 7.3, such that the interconnecting gas channel 4.3 surrounds the hot gas channel 7. With a large floor area of the storage space, it may be advantageous to use multiple interconnecting gas channels 4.3 and hot gas channels 7.

Further, the technological area 4.2 may be connected to at least one outlet heat exchanger 12. The outlet heat exchanger 12 is preferably connected by a coaxial heat outlet 7.2, wherein the higher temperature gas channel is within the lower temperature gas channel. Further, the technological area 4.2 may be connected to at least one inlet heat exchanger 11. The input heat exchanger 11 is preferably connected by a coaxial heat input-output 7.3.

The gas gap 4.1 is further connected on the bottom side to the maintenance area 22 and to the air channel 13.3. This air channel 13.3 is connected to a heat-insulating two-way valve 13, which is further connected to a safety gas inlet channel 13.2. The two-way valve 13 may be connected via a magnetic coupling 15.4 to a servomotor valve drive 15.3.

The load-bearing inner shell 3 defines the high-temperature storage space 14 around the internal volume of the heat storage and is formed of a material sufficiently tight and load bearing to maintain the shape of the bulk-filled storage volume, such as monolithic concrete, tightly bonded precast concrete sections, steel plate, ceramic sections, dense sufficiently heat-resistant fibrous composite panels, and combinations of these materials. The load-bearing inner shell 3 is also the load-bearing structure of the heat storage and is formed as a secondary thermal storage layer. On the inner side of the load-bearing inner shell 3, adjacent to the high-temperature storage space 14, the high-temperature thermal insulation 2 is arranged defining the high-temperature storage space 14 in which the bulk refractory material 1 is arranged.

The floor area and height of the high-temperature storage space 14 is derived from both the design capacity and a suitable ratio to ensure that the surface area of the average hot storage volume 14.4 is minimized, and from the suitable height of the entire high-temperature storage space 14. This is due to the need to meet the condition of at least twice, optimally 4 to 8 times, the height of the steep thermal gradient region 14.3, defined as the region in which the flowing gas changes 90% of the temperature difference

between the mean temperature of the cooled storage space 14. The height of the steep thermal gradient region 14.3 increases with the velocity of the gas flow (Figure 2), and decreases at the same velocity as the particle size of the bulk refractory material decreases (Figure 3). The height of the steep thermal gradient region 14.3 is calculated
5 using Ergun's equation of flow in the porous zone, and the heat sharing equations in the mathematical-physical model. The proposed mean particle size of the bulk refractory material 1 filling the high temperature storage space 14 corresponds to 1/1500 to 1/6000 of its height, with a maximum particle size difference in a particular application of up to 5:1.

10 Among natural materials, the bulk refractory material 1 can be considered mainly microcrystalline leachable rocks with a minimum of alkaline impurities, such as basalt, andesite, dacite, etc. Among artificial materials, ceramic sintered aggregates with a high bulk density and spherical particle shape are particularly suitable. For special applications with temperatures above 1200 °C, a sufficiently solid form of carbon (e.g. pellet-pressed
15 graphite with glassy carbon on the surface) or its compounds in the form of carbides and nitrides can be used. Advantageous overall properties can also be achieved by mixing or layering particles of similar fraction but with different material properties (e.g. in terms of bulk density and thermal conductivity).

The high-temperature thermal insulation 2 can be made as a layered insulation that uses
20 refractory and high-temperature insulation materials. In addition to price, refractory materials differ significantly in thermal resistance and thermal insulation properties. From the inner to the outer face of the insulation, the internal local temperature in the insulation decreases. Insulations with excellent performance at high temperatures are up to several times more expensive than thermal insulations that are only effective at lower
25 temperatures. It is therefore advisable to divide the overall thermal insulation into layers operating over a certain temperature range. The materials of the individual layers can then be designed with respect to the calculated maximum local temperature. The resulting cost and thickness of the thermal insulation can thus be optimised. Microporous ceramic insulations (e.g. opacified mixtures of pyrogenic silica with silicon carbide or
30 titanium dioxide, e.g. branded as FREEFLOW from PROMAT) are the most effective at high temperatures. However, a cheaper material with inferior properties (e.g. expanded perlite and/or expanded vermiculite) may be more cost effective.

Thermal insulations do not have high mechanical resistance. For practical use in heat

storage, it is necessary to bind them inside a pressure- and abrasion-resistant material. A layer assembled using ground insulating ceramic bricks (e.g. branded as POROTHERM with cavities filled with expanded perlite on the outside and microporous insulation on the inside) can be ideal for temperatures of 500-1200 °C. For smaller-scale applications, mechanically low-resistant high-temperature insulations can be protected by a tight surface layer, e.g. made of heat-resistant sheet metal (e.g. heat-resistant, alloyed, stainless, austenitic steel of class 1.4828 according to AISI 309, CSN 17251). More advantageous thermal insulation properties can also be achieved by vacuuming the layer.

For layers at lower operating temperatures on the outside of high temperature insulation (at local temperatures up to 500-600 °C), significantly cheaper mineral and ceramic fibre materials (e.g. stone wool board branded as ORSTECH 100 from ISOVER) are already effective.

The thermal-insulating outer shell 5 may comprise mutually sealed prefabricated elements with a sandwich construction (shell - insulation core - shell), anchored to the load-bearing inner shell 3 with a spacing forming the air gap 4.1, e.g. industrially produced sandwich panels of the sheet metal – wool – sheet metal type.

Preferably, at least one enclosure 8.1 for an electrically heated element 8.2 is arranged inside the upper part of the high-temperature thermal insulation 2, which is connected to the hot gas channel 7 on the lower side and to the gas layer 14 on the upper side. The enclosure 8.1 has an outlet on the outer face of the thermal-insulating outer shell 5 and its inner part is filled with thermal insulation material from the outlet to the inner face of the high-temperature thermal insulation 2. At least one electrically heated element 8.2 (e.g. a resistor, induction heater) is arranged in the enclosure 8.1 and is connected to the power source 8.

Inside the technological area 4.2, there is a blower system 10 that comprises a combination of at least two blowers that allow flow in one inlet heat transfer circuit 9.1 or 9.3 and one outlet heat transfer circuit 9.2. Preferably, the blower system 10 also comprises additional valves and blowers to allow simultaneous operation and interconnection of multiple heat exchanging circuits. The drives 15.5 of the blowers and any servomotor valve drives 15.3 are preferably located on the outside of the heat-insulating outer shell 5.

Heat exchanging circuits

The blower system 10 provides gas flow in at least one inlet and one output heat exchanging circuit (Figure 4), where the input heat exchanging circuit may be an input heat exchanging circuit 9.1 or an input heat exchanging circuit 9.3 with electric heating.

5 Preferably, the blower system 10 provides flow in the output heat exchanging circuit 9.2 or the output heat exchanging circuit 9.4 with output temperature control, and/or in a combination 9.5 of heat exchanging circuits with predominance of inputs and in a combination 9.6 of heat exchanging circuits with predominance of outputs. Preferably, the blower system 10 allows in these combination heat exchanging circuits (9.5 and 9.6) to

10 reduce the output temperature in the output heat exchanger 12. With all heat exchanging circuits operating, the electrically heated element 8.2 can supply heat. A diagram of the heat exchanging circuits is shown in Figures 4a to 4f.

The input heat exchanging circuit 9.1 (Figure 4a) represents the connection of the blower system 10, on the suction side, sequentially with the technological area 4.2, the

15 interconnecting gas channel 4.3, the inlet-outlet 6 of the cooled gas, the gas gap 4.1, the dust separator 20.1, and the grid with gas channels 14.7 under the high-temperature storage space 14. On the outlet side, the blower system 10 is sequentially connected to the first outlet channel 10.1, the inlet heat exchanger 11, the first inlet channel 11.1, the hot gas channel 7, and the hot gas layer 14.6 above the high-temperature storage space

20 14, wherein the enclosure 8.1 with the electrically heated element 8.2 is preferably arranged between the termination of the hot gas channel 7 and the hot gas layer 14.6.

The output heat exchanging circuit 9.2 (Figure 4b) represents the connection of the blower system 10, on the suction side, sequentially to the second inlet gas channel 10.2, the outlet heat exchanger 12, the second outlet channel 12.1, the hot gas channel 7 and

25 the hot gas layer 14.6 above the high-temperature storage space 14, wherein the enclosure 8.1 with the electrically heated element 8.2 is preferably arranged between the termination of the hot gas channel 7 and the hot gas layer 14.6. On the outlet side, the blower system 10 is successively connected to the technological area 4.2, the interconnecting gas channel 4.3, the cooled gas inlet-outlet 6, the gas gap 4.1, the dust

30 separator 20.1, and the grid with gas channels 14.7 below the high-temperature storage space 14.

The input heat exchanging circuit 9.3 with electric heating (Figure 4c) represents the

connection of the blower system 10, on the suction side, sequentially with the technological area 4.2, the interconnecting gas channel 4.3, the inlet-outlet 6 of cooled gas, the gas gap 4.1, the dust separator 20.1, the grid 14.7 with gas channels. On the outlet side, the blower system 10 is successively connected to the second interconnecting
5 gas channel 10.3, the hot gas channel 7, the enclosure 8.1 with the electrically heated element 8.2 and the hot gas layer 14.6 above the high-temperature storage space 14.

The other heat exchanging circuits (9.4, 9.5, 9.6) use only the physical connection of the input and output heat exchanging circuits described above (9.1, 9.2, 9.3).

Additional functions and control

10 A distribution valve 16 is used as an inlet for refilling the bulk refractory material, its location is always above the hot gas layer 14.6, wherein in the case of a large floor area of the storage tank it may be advantageous to use more than one distribution valve 16.6. A vibration plate 18 is mounted at the lower part 17.6 of the inner body of the distribution valve in the space of the hot gas layer 14.6. The distribution valve comprises electrically
15 actuated elements in the form of a servomotor valve drive 15.3, a vibrator 15.8 and an electromagnetic coupling 17.7 of the distribution valve, connected downstream of a thermal fuse 15.6. The internal structure and function of the distribution valve 16 is illustrated in Fig. 5 and is described in a separate description, see below. The distribution valve 16 is connected to a bulk refractory material transport system 19 via a
20 replenishment channel 19.3. In case more than one distribution valve 16 is used, the replenishment channel 19.3 is routed from the distributor 19.1 and this is then connected to the bulk refractory material transport system 19.

The exemplary high-temperature heat storage system also comprises a measurement and control system comprising a control unit 15.1 which is connected both to the power
25 supply 8 and to the drives 15.5 and servomotor drives of the blower system 10, via the thermal fuse 15.6 to the electromagnetic coupling 15.4 and the servomotor valve drive 15.3, then to the electrically operated elements of the distribution valve 16 via the thermal fuse 15.6 to the servomotor valve drive 15.3, the vibrator 15.8, and to the electromagnetic coupling 17.7 of the distribution valve. When more than one distribution valve 16 is used,
30 the control unit is preferably also connected to the distributor servomotor drive 19.2, the bulk refractory material transport system 19, and monitors the pressure drop of the dust separator 20.1 and controls its regeneration, controls the collection and transport system

20 for separated dust, and controls the collection and transport system 21 for material to be reprocessed.

Further, the control unit 15.1 is connected to temperature sensors 15.2 arranged in the first gas outlet channel 10.1 and the first gas inlet channel 11.1, to temperature sensors
5 15.2 arranged in the second gas inlet channel 10.2 and the second gas outlet channel 12.1, and to temperature sensors 15.2 arranged in the space of the cooled gas inlet-outlet 6. Preferably, the control unit is connected to the temperature sensors 15.2 at the connection point of the enclosure 8.1 to the gas layer 14.6, and at the connection point of the enclosure 8.1 to the hot gas channel 7.

10 The control unit 15.1 is further connected to an accelerometer 15.9 in the distribution valve 16 and preferably is also connected to a flow and differential pressure meter 15.7 in the first gas outlet channel 10.1.

Operation of a high-temperature heat storage system

The high-temperature heat storage function is implemented by means of heat exchanging
15 circuits with gas as the working medium, schematically shown in Figure 4. The heat exchanging circuits are operated by the blower system 10. The operating temperature of the blower system 10 is determined by the temperature in the technological area 4.2, which is derived from the temperature of the gas in the second gas inlet channel 10.2, and the temperature in the gas gap 4.1.

20 The heat storage system operates in at least two heat exchanging circuits, one of which transfers heat to the storage system and the other transfers heat to the outgoing gas. The outlet heat exchanging circuit 9.2 transfers heat from the heat storage to the outlet heat exchanger 12. The transfer of heat to the storage medium may be via two heat exchanging circuits, the inlet heat exchanging circuit 9.1 or the inlet heat exchanging
25 circuit 9.3 with electrical heating. Advantageously, it may be possible to reduce the outlet temperature of the gas stream to the outlet heat exchanger 12, implementable via the heat exchanging circuit 9.4 with outlet temperature control. A further advantage may be the ability of the storage to provide various simultaneous power combinations of heat input and heat output from the storage, a combination of heat exchanging circuits 9.5 may
30 operate in this manner.

- The input heat exchanging circuit 9.1, transferring heat to the gas stream in at least one input heat exchanger 11, is activated when heat is supplied to the input heat exchanger

11 or when electricity is simultaneously supplied to the electrically heated element 8.2. The blower system 10 draws gas from the technological area 4.2 and displaces it through the first gas outlet channel 10.1 into the input heat exchanger 11. Advantageously, the first outlet gas channel 10.1 and the first inlet gas channel 11.1
5 from the inlet heat exchanger 11 are carried by a coaxial pipe line in the form of a heat input 7.1. The pressure gradient created by the blower system 10 allows gas to flow through the high-temperature heat storage and simultaneously in the inlet heat exchanger 11. The hot gas from the first gas inlet 11.1 flows into the hot gas channel 7 and may further flow through the enclosure 8.1 past the electrically heated element 8.2,
10 where the gas temperature is further increased when the electric power is actively supplied, if any. It then enters the hot gas layer 14.6 above the high temperature accumulation volume 14 into the bulk refractory material 1 at the top of the hot accumulation volume 14.4. After passing through the hot accumulation volume 14.4, it enters the steep thermal gradient region 14.3 where it transfers heat to the bulk
15 refractory material 1. The gas further flows into the cooled accumulation volume 14.5 and, after passing through the cooled accumulation volume 14.5 at its base, flows into the grid with gas channels 14.7, arranged around the load-bearing inner shell 3 of the high-temperature storage space 14, wherein the gas gap 4.1 is connected by the inlet-outlet 6 of the cooled gas and the connecting channel 4.3 to the technological area 4.2,
20 thus closing the gas flow circuit.

- The output heat exchanging circuit 9.2, transferring heat to the gas stream in at least one output heat exchanger 12, is activated when heat is demanded. The blower system 10 draws gas from the second inlet gas channel 10.2 and displaces the gas into the technological area 4.2. Preferably, the second inlet gas channel 12.1 and the second
25 outlet gas channel 10.2 from the outlet heat exchanger 12 are routed through a coaxial channel, in the form of the heat output 7.2. The pressure gradient created by the blower system 10 allows gas to flow through the high-temperature heat storage and simultaneously in the outlet heat exchanger 12. The cooled gas flows into the technological area 4.2, the interconnecting channel 4.3, then through the inlet-outlet 6
30 of the cooled gas into the gas gap 4.1 which surrounds the load-bearing inner shell 3. The cooled gas is preheated by passing around the load-bearing inner shell 3. It then passes (as a reverse flow without necessary effect) through the dust separator 20.1, the grid with gas channels 14.7, and enters the bulk refractory material 1 at the bottom of the cooled storage volume 14.5 After passing through the cooled accumulation

volume 14.5, in the steep thermal gradient region 14.3, it receives heat from the bulk refractory material 1, and further passes through the hot accumulation volume 14.4 into the hot gas layer 14.6. It may further pass through the enclosure 8.1, past the electrically heated element 8.2. It then enters the hot gas channel 7 and the outlet gas channel 12.1. After passing through the outlet heat exchanger 12, the cooled gas returns through the second inlet gas channel 10.2, thus completing the circuit.

- The input heat exchanging circuit 9.3 from electricity, transferring heat to the gas stream in at least one electrically heated element 8.2, is activated when electricity is supplied to the electrically heated element 8.2. The blower system 10 draws gas from the technological area 4.2 and displaces it through the second interconnecting gas channel 10.3 into the hot gas channel 7, further flowing through the enclosure 8.1 around the electrically heated element 8.2 and enters the hot gas layer 14.6 above the high temperature accumulation volume 14 into the bulk refractory material 1 on the upper side of the hot accumulation volume 14.4. After passing through the hot accumulation volume 14.4, it enters the steep thermal gradient region 14.3 where it transfers heat to the bulk refractory material 1. The gas further flows into the cooled accumulation volume 14.5 and, after passing through the cooled accumulation volume 14.5 at its base, flows into the grid with gas channels 14.7. The gas further flows through the dust separator 20.1 into the gas gap 4.1 arranged around the load-bearing inner shell 3 of the high temperature storage space 14, wherein the gas gap 4.1 is connected by the inlet-outlet 6 of the cooled gas and the connecting channel 4.3 to the technological area 4.2, thus closing the gas flow circuit.

Preferably, the storage also works in these heat exchanging circuits:

- Outlet heat exchanging circuit 9.4 with output temperature control, transferring heat to the gas stream in the same way as in the outlet heat exchanging circuit 9.2, but with the addition of the functionality of the blower system 10. The blower system 10 will preferably at the same time additionally provide continuous control of the gas flow from the technological area 4.2, through the second interconnecting gas channel 10.3 to the hot gas channel 7.
- a combination 9.5 of heat exchanging circuits, transferring heat to the gas stream in the same way as in the input heat exchanging circuit 9.1, and at the same time in the same way as in the output heat exchanging circuit 9.2, but with the addition of the functionality

of the blower system 10. The blower system 10 will preferably additionally provide continuous control of the gas flow into the first outlet channel 10.1, continuous control of the gas flow from the second inlet channel 10.2, and continuous control of the gas flow from the technological area 4.2, through the second interconnecting gas channel 10.3, into the hot gas channel 7.

The cooled gas is preheated by the thermal energy passing through the high-temperature thermal insulation 2 into the high temperature inner shell 3 by passing around the high temperature inner shell 3 before entering the inlet heat exchanger 11. The mass of the load-bearing inner shell 3 accumulates this heat energy for a limited time, this time, on the order of units, at most tens of hours (determined by the temperature rise limit and the ratio of the heat capacity of the load-bearing inner shell to the heat flux through the high temperature heat insulation), which is the maximum break in the operation of the outlet heat exchanger 12. This time is determined by the ratio of the heat capacity of the load-bearing inner shell 3 and the heat flux through the high-temperature thermal insulation 2 and the limiting temperature in the gas gap 4.1 and technological area 4.2.

Neither the inner side of the thermal-insulating outer shell 5, nor the gas gap 4.1, nor the technological area 4.2 is exposed to extreme temperatures when the measurement and control system is functioning properly, only to temperatures elevated compared to the temperature of the returning cooled gas from the outlet heat exchanger 12. The degree of possible temperature increase in technological area 4.2 is determined by the thermal resistance of the blower construction, and the thermal-insulating outer shell 5. In the event of malfunction or failure of the measurement and control system, the power supply to the electromagnetic coupling 15.4, and the servomotor valve drive 15.3 is automatically disconnected by the thermal fuse 15.6. The two-way valve 13 simultaneously opens the connection between the safety outlet gas channel 13.1 and the interconnecting gas channel 4.3 and between the air channel 13.3 and the safety inlet gas channel 13.2. The hot gas in the gas gap 4.1 and the maintenance area 22 is then vented by gravity fall. The effectiveness of the ventilation can be enhanced by a "chimney effect", which consists of extending the safety gas outlet channel 13.1 above the level of the thermal-insulating outer shell 5.

The control unit 15.1 will also deal with the continuous evaluation of pressure loss changes during gas flow in the high-temperature storage space 14. For this operation, the control unit 15.1 will be connected to the flow and differential pressure meter 15.7,

measuring the pressure difference between the gas in the first outlet channel 10.1 and the gas in the technological area 4.2, during the operation of the inlet heat exchanging circuit 9.1, or between the gas in the second connection channel 10.3 and the gas in the technological area 4.2, during the operation of the inlet heat exchanging circuit 9.3 with electric heating.

Handling of bulk refractory material

When the above-normal pressure drop is measured, the need for replacement (reprocessing) of the bulk refractory material 1 will be signalled. The replacement will be initiated by the operation of the collection and transport system 21 for bulk refractory material under at least one hopper 21.1. With large storage areas, it will be advisable to design multiple hoppers 21.1 so that the sloping walls of the hopper 21.1, with sufficient gradient, do not increase the necessary height of the maintenance area too much. When the bulk refractory material 1 is removed uniformly, the material will slump uniformly throughout the cross-sectional area of the high-temperature storage space 14 through the grid with gas channels 14.7, and the height of the hot gas layer 14.6 will be increased.

The distribution valve 16 and its operation is described in Figure 5. The uniform distribution of particles of the bulk refractory material around the distribution valve 16 will be provided by a vibration plate 18, mounted on the lower part 17.6 of the inner body of the distribution valve in the hot gas layer 14.6. The vibration plate 18 will be at a slight incline from the mouth of the distribution valve 16 to the edges, and thus particles will be distributed throughout its entire surface until the holes are filled, with no possibility of particles being retained in the mouth of the distribution valve 16 before almost completely filling the space around the perimeter of the vibration plate 18. The eccentricity of the vibration of the plate, as defined by the accelerometer 15.9, will indicate the degree of its contact with the grains of the bulk refractory material 1. The eccentricity of vibration is understood to be the range of extreme positions when the plate is vibrating, i.e. at constant excitation energy the magnitude of the acceleration of the mass of the plate during vibratory motion will decrease as the number of particles in contact with the vibration plate increases. At a high particle contact rate with the vibration plate 18, the eccentricity of the motion of the vibration plate 18 will be reduced, thereby signalling a state of filling of the high-temperature storage space 14. The vibration plate 18 must be made of a suitable refractory material with respect to the operating temperatures and mechanical loads.

The refractory bulk material 1 to be reprocessed may be conveyed to at least one distribution valve 16 by means of the bulk refractory material transport system 19, and by means of the replenishment channel 19.3 with sufficient slope to allow free movement of particles driven by gravity or vibration. In the case of a system with more than one
5 distribution valve 16, the bulk refractory material transport system 19 will be provided with the distributor 19.1 with the distributor servomotor drive 19.2 controlling the distribution of particles to the individual distribution valves 16.

In particular, during the operation of the input heat exchanging circuit 9.1, and thus during storing of thermal energy in the storage, the gas flow may entrain detached dust particles.
10 This is due to the erosive effect of large temperature changes and associated changes in particle size. The gas flow through the bulk refractory material 1 will be terminated at the bottom of the high-temperature storage space 14 by a gas inlet into the grid with gas channels 14.7. From here, the gas will be directed to at least one dust separator 20.1 before entering the gas gap 4.1. Preferably, the dust separator 20.1 will be of a cyclone
15 design, ensuring maximum uniformity and minimum pressure loss. In order to capture even very fine particles, the cyclone dust collector 20.1 may also be equipped with a filter with the possibility of recovery, and a differential pressure sensor 20.2 connected to the control unit 15.1. (An effective method of filter recovery may be provided by adding a vibrator and activating it in the event of a weak counterflow resulting from the operation
20 of the output heat exchanging circuit 9.2).

The maintenance area 22 is located under the high-temperature storage space. This area is intended for maintenance or servicing of the collection and transport system 20 for separated dust, at least one dust separator 20.1 and the collection and transport system 21 for material to be reprocessed. Particularly for larger floor plans, an automated design
25 of the collection and transport systems is preferable, where only occasional servicing by maintenance equipment will be required. The maintenance area 22 will preferably be comprised in the space insulated by the thermal-insulating outer shell 5. The temperature in the maintenance area 22 may reach levels that do not allow direct human operation during normal operation of the storage facility. For service intervention, it will be necessary
30 to reduce the temperature in this space to a level acceptable for human operation. This will be accomplished by opening the two-way valve 13 to provide a vent for the cooled gas (which may be at a high temperature for human operators) and, if necessary, a supply of ambient air. In order to facilitate the maintenance of an acceptable temperature for the

human operator, the ceiling of the maintenance area 22 will preferably be provided with thermal insulation of the maintenance area 5.2.

Distribution valve function

Figure 5 shows schematically the structure of the distribution valve and its working position. An exemplary arrangement describes the addition of bulk refractory material 1 to the hot gas layer 14.6 above the high-temperature storage space 14 at operating temperature. The exemplary solution prevents heat transfer and ensures the safety of the valve when entering the high temperature region. In the exemplary solution of the distribution valve 16, an electromechanical system is used. For a larger number of distribution valves 16, a similar solution can be provided in the form of a hydraulic system.

The distribution valve 16 comprises a cylindrical distribution valve housing 17 having a vertical axis, into which a replenishment channel 19.3 is routed at its upper end. Inside the cylindrical distribution valve housing 17, a servomotor drive housing 17.2 having a smaller outer diameter is built (at least 6 times the particle diameter), in which the upper part 17.3 of the inner body of the distribution valve body having a spring hinge 17.8 moves. A movable part of the primary shut-off element 17.4 of the distribution valve is attached externally to the upper part 17.3 of the inner body of the distribution valve, which in the closed state (in the upper position) fills the space between the distribution valve housing 17 and the servomotor drive housing 17.2. The upper part 17.3 of the inner body of the distribution valve is separated from the lower part 17.6 of the inner body of the distribution valve by a vibration damper 17.5 below the connection of the primary shut-off element 17.4 of the distribution valve. The lower part 17.6 of the internal body of the distribution valve is shaped like a conical section with a wide horizontal base on the lower side and a narrow upper part connected to the vibration damper 17.5 and is made of a solid thermal insulating material (e.g. porous ceramic). A vibrator 15.8 and an accelerometer 15.9 are mounted inside the lower part 17.6 of the inner body of the distribution valve, at its upper end with minimal thermal influence.

The distribution valve housing 17 transitions on the lower side into the distribution valve insulation shell 17.1, following the outer surface of the lower part 17.6 of the inner body of the distribution valve. The distribution valve insulation shell 17.1 passes through the thermal-insulating outer shell 5, the gas gap 4.1, the load-bearing inner shell 3, and the high-temperature thermal insulation 2. At the levels of the layers of the high-temperature

thermal insulation 2, rings of sealing insulating material are fitted into the grooves in the distribution valve insulation shell 17.1. At the level of the gas gap 4.1, holes are provided in the distribution valve insulation shell 17.1 connecting the gas gap 4.1 with the sealing gap formed in the intermediate position 16.2 of the distribution valve and the open
5 distribution valve 16.3. The size of the openings will be just large enough so that the flow of cooled gas from the gas gap 4.1 so connected into the hot gas layer 14.6, created by the pressure differential in the operation of the heat exchanger outlet circuit 9.2, will sufficiently block the spread of heat to the top of the distribution valve 16. The spring hinge 17.8 will exert sufficient force on the coupled upper part 17.3 of the inner body of
10 the distribution valve and the lower part 17.6 of the inner body of the distribution valve, further coupled to the vibration plate 18, to compensate for their combined weight and, in addition, exert sufficient sealing pressure on the distribution valve insulation shell 17.1.

The distribution valve 16 will perform its function by the vertical movement of the lower part 17.6 of the inner body of the distribution valve and other parts firmly connected
15 together, in particular the primary shut-off element 17.4 of the distribution valve, the upper part 17.3 of the inner body of the distribution valve, the vibration damper 17.5, the vibrator 15.8 and the accelerometer 15.9. The vertical movement is provided by the servomotor valve drive 15.3, the feed brake 17.9 and the spring hinge 17.8.

The distribution valve 16 has three operating positions. In the first position, the closed
20 distribution valve 16.1, the lower part 17.6 of the inner body of the distribution valve engages the seal in the distribution valve insulation shell 17.1 and the primary shut-off element 17.4 of the distribution valve is closed. The closure of the primary shut-off element 17.4 of the distribution valve need not be tight, it need only restrain the movement of particles of the bulk refractory material 1.

25 In the second operating position, the intermediate position 16.2 of the distribution valve, there is a gap between the lower part 17.6 of the inner body of the distribution valve and the distribution valve insulation shell, allowing, with a margin, the free passage of particles of the bulk refractory material 1, but not allowing their passage through the primary shut-off element 17.4 of the distribution valve.

30 In the third position, the open distribution valve 16.3, the primary shut-off element 17.4 of the distribution valve is also opened, and particles of the bulk refractory material 1 fall through the distribution valve 16 into the hot gas layer 14.6.

The servomotor valve drive 15.3 is designed in such a way that when the power supply is interrupted (even in the event of a random emergency), an external force will enable its closure by interrupting the power supply to the electromagnetic coupling 16.4 of the distribution valve. The valve closure time between the phase of the intermediate position 5 16.2 of the distribution valve and the reduction of the gap between the distribution valve insulation shell 17.1 and the lower part 17.6 of the inner body of the distribution valve below the particle size dimension of the bulk refractory material 1 shall be sufficient to allow the passage of particles from the primary shut-off element 17.4. With sufficient clearance in the hot gas layer 14.6, particles of the bulk refractory material 1 will not be 10 trapped within the distribution valve 16. The size of the inlet opening from the replenishment channel 19.3 into the distribution valve 16 is just large enough to prevent plugging of the open distribution valve 16.3.

In the exemplary design of the distribution valve 16, the adjustable closing speed is ensured by the combination of the hydrodynamic feed brake 17.9 and the spring hinge 15 17.8. The valve closure occurs even if the temperature inside the distribution valve housing 17 rises above the design limit, when the activation of the thermal fuse 15.6 disables the power supply. The disconnection of the electromagnetic coupling 16.4 of the distribution valve causes the drive to disengage from the upper part 17.3 of the inner body of the distribution valve, thus slowly closing the valve due to the fixed setting of the feed 20 brake 17.9. The vibration damper 17.5 separates the static part of the valve from the vibrating lower part 17.6 of the inner body of the distribution valve.

Industrial applicability

The high-temperature heat storage can be used to transfer the heat of a gas medium that is stable and chemically unreactive even at high temperatures, such as nitrogen or air. 25 The heat energy can be stored in the bulk refractory material.

List of reference signs

	1	bulk refractory material
	2	high-temperature thermal insulation
	3	load-bearing inner shell
5	3.1	base plate
	4.1	gas gap
	4.2	technological area
	4.3	interconnecting gas channel
	5	thermal-insulating outer shell
10	5.1	load-bearing thermal insulation
	5.2	thermal insulation of the maintenance area 22
	6	cooled gas inlet-outlet
	7	hot gas channel
	7.1	heat input
15	7.2	heat output
	7.3	heat input-output
	8	power source
	8.1	enclosure
	8.2	electrically heated element
20	9.1	input heat exchanging circuit
	9.2	output heat exchanging circuit
	9.3	input heat exchanging circuit with electric heating
	9.4	output heat exchanging circuit with output temperature control
	9.5	heat exchanging circuit combination
25	10	blower system
	10.1	first outlet gas channel
	10.2	second inlet gas channel
	10.3	second interconnecting gas channel
	11	inlet heat exchanger
30	11.1	first inlet gas channel
	12	outlet heat exchanger

	12.1	second outlet gas channel
	13	two-way ventilation valve
	13.1	safety outlet gas channel
	13.2	safety inlet gas channel
5	13.3	air channel
	14	high-temperature storage space
	14.1	hot gas flow
	14.2	cooled gas flow
	14.3	steep thermal gradient region
10	14.4	hot storage volume
	14.5	cooled storage volume
	14.6	hot gas layer
	14.7	grid with gas channels
	15.1	control unit
15	15.2	temperature sensor
	15.3	servomotor valve drive
	15.4	electromagnetic coupling
	15.5	drive
	15.6	thermal fuse
20	15.7	flow and differential pressure meter
	15.8	vibrator
	15.9	accelerometer
	16	distribution valve
	16.1	closed distribution valve
25	16.2	intermediate position of the distribution valve
	16.3	open distribution valve
	17	distribution valve housing
	17.1	distribution valve insulation shell
	17.2	servomotor drive housing
30	17.3	upper part of the inner body of the distribution valve
	17.4	primary shut-off element of the distribution valve
	17.5	vibration damper

	17.6	lower part of the inner body of the distribution valve
	17.7	electromagnetic coupling of the distribution valve
	17.8	spring hinge
	17.9	feed brake
5	18	vibration plate
	19	bulk refractory material transport system
	19.1	distributor
	19.2	distributor servomotor drive
	19.3	replenishment channel
10	20	collection and transport system for separated dust
	20.1	dust collector
	20.2	differential pressure sensor
	21	collection and transport system for material to be reprocessed
	21.1	hopper
15	22	maintenance area

PATENT CLAIMS

1. A system for storing and transferring heat, comprising
- a. at least one heat source for generating thermal energy;
 - 5 b. a high-temperature heat storage with a bulk refractory material (1) filling a high-temperature storage space (14) for storing the generated thermal energy;
 - c. at least one heat consumption system for using the stored thermal energy; and
 - d. a heat transfer mechanism for transferring heat from the heat source to the high-temperature heat storage system and from the high-temperature heat storage system to the heat consumption system, wherein the heat transfer mechanism is a closed gas circuit connecting the heat source, the high-temperature heat storage system and the heat consumption system, wherein the high-temperature heat storage system is partially enclosed by a load-bearing inner shell (3),
 - 10 **characterized in that** the bulk refractory material (1) comprises a particle fraction having a sphericity in the range of 0.4 to 1 and a mean particle size in the range of 0.5 to 20 mm, wherein the ratio of the volume of the largest to the smallest particles is at most 5:1,
 - 15 wherein the load-bearing inner shell (3) is enclosed with a thermal-insulating outer shell (5) such that a gas gap (4.1) is arranged between the load-bearing inner shell (3) and the thermal-insulating outer shell (5) for recovering heat loss from the high-temperature heat storage, penetrating through the load-bearing inner shell (3), wherein the gas gap (4.1) together with an interconnecting gas channel (4.3) connects the high-temperature heat storage to at least one technological area (4.2) which is further connected to at least one heat consumption system, wherein a hot gas channel (7) connects the high-temperature heat storage to at least one heat source.
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2. The system according to claim 1, **characterized in that** the load-bearing inner shell (3) comprises a high-temperature thermal insulation (2) on the side adjacent to the high-temperature storage space (14).

3. The system according to any one of the preceding claims, **characterized in that** the heat source is an inlet heat exchanger (11), wherein a blower system (10) is arranged in the technological area (4.2) for conducting cooled gas from the high-temperature storage space (14) through the gas gap (4.1), the interconnecting gas channel (4.3),
5 the technological area (4.2) and a first outlet gas channel (10.1) to at least one inlet heat exchanger (11), wherein for conducting hot gas from the inlet heat exchanger (11), at least one hot gas channel (7) is arranged for conducting hot gas from the inlet heat exchanger (11) to a gas layer (14.6) above the high-temperature storage space (14);
- 10 and/or **characterized in that** the heat source is at least one electrically heated element (8.2), wherein a blower system (10) is arranged in the technological area (4.2) for conducting cooled gas from the high-temperature storage space (14) through the gas gap (4.1), the interconnecting gas channel (4.3) and the technological area (4.2) to a second interconnecting gas channel (10.3) and the hot gas channel (7), and
15 further in thermal contact with the electrically heated element (8.2) for heating the gas to the gas layer (14.6) above the high-temperature storage space (14), wherein the electrically heated element (8.2) is arranged inside the load-bearing inner shell (3) outside the high-temperature storage space (14), preferably in the hot gas channel (7);
- 20 and further **characterized in that** the heat transfer system is an outlet heat exchanger (12), wherein a blower system (10) is arranged in the technological area (4.2) for conducting cooled gas from the outlet heat exchanger (12) through a second gas inlet channel (10.2), the technological area (4.2), the interconnecting gas channel (4.3) and the gas gap (4.1) to the high-temperature storage space (14), wherein for conducting
25 hot gas from the high-temperature storage space (14), at least one hot gas channel (7) is arranged to lead from the gas layer (14.6) above the high-temperature storage space (14) to at least one outlet heat exchanger (12).
4. The system according to any one of the preceding claims, **characterized in that** the first inlet gas channel (11.1) and the first outlet gas channel (10.1) are arranged
30 coaxially with each other such that the first outlet gas channel (10.1) surrounds the first inlet gas channel (11.1); and/or **characterized in that** the second inlet gas channel (10.2) and the second output gas channel (12.1) are arranged coaxially with

each other, such that the second input gas channel (10.2) surrounds the second output gas channel (12.1); and/or **characterized in that** the interconnecting gas channel (4.3) and the hot gas channel (7) are arranged coaxially with each other, such that the interconnecting gas channel (4.3) surrounds the hot gas channel (7).

- 5 5. The system according to any one of the preceding claims, **characterized in that** the gas gap (4.1) is connected via an air channel (13.3) to a two-way valve (13), wherein the two-way valve (13) is further connected to the surroundings via a safety inlet gas channel (13.2) and a safety outlet gas channel (13.1).
- 10 6. The system according to any one of the preceding claims, **characterized in that** the bulk refractory material (1) is any one from the group comprising basalt, andesite, dacite, artificial sintered aggregate, ceramic material, blast furnace slag, compressed graphite with glassy carbon on the surface, carbide and nitride.
- 15 7. The system according to any one of the preceding claims, **characterized in that** a temperature sensor (15.2) is arranged in the first gas inlet channel (11.1), in the first gas outlet channel (10.1), in the second gas inlet channel (10.2), in the second gas outlet channel (12.1), in the space of the cooled gas inlet-outlet (6), in the space where an enclosure (8.1) of the electrically heated element (8.2) connects to the gas layer (14.6) above the high-temperature storage space (14), and in the space of the hot gas channel (7) upstream of the inlet to the enclosure (8.1), wherein each temperature
20 sensor (15.2) is connected to a control unit (15.1).
8. The system according to any one of the preceding claims, **characterized in that** a maintenance area (22) is arranged under the high-temperature storage space (14) for housing a collection and transport system (20) for separated dust and/or for housing a collection and transport system (21) for material to be reprocessed.
- 25 9. The system according to any one of the preceding claims, **characterized in that** at least one distribution valve (16) for the inlet of the bulk refractory material (1) at operating temperatures of the high-temperature heat storage space (14) enters into the gas layer (14.6) above the high-temperature heat storage space (14).
- 30 10. The system according to any one of the preceding claims, **characterized in that** the mean particle size is in the range of 0.5 mm to 20 mm, wherein the ratio of the mean

particle size of the bulk refractory material (1) to the total height of the high-temperature storage space (14) is in the range of 1:1500 to 1:6000.

11. A method of storing and transferring heat using the system according to any one of the preceding claims, wherein a high-temperature heat storage is partially enclosed by a load-bearing inner shell (3) and the load-bearing inner shell (3) is enclosed by a thermal-insulating outer shell (5) such that a gas gap (4.1) is provided between the load-bearing inner shell (3) and the thermal-insulating outer shell (5),

wherein the method comprises the following steps of heat storage:

- a. generating thermal energy in at least one heat source to form hot gas;
- 10 b. transferring the hot gas from the heat source to the high-temperature heat storage by means of a closed gas circuit as a heat transfer mechanism;
- c. storing the generated thermal energy from the hot gas in the high-temperature heat storage with a bulk refractory material (1) comprised in the high-temperature storage space (14) to form a cooled gas;
- 15 d. transferring the cooled gas from the high-temperature heat storage to the heat source by means of the closed gas circuit as the heat transfer mechanism; and
- e. optionally repeating steps a. to d.;

wherein the method further comprises the following steps of stored heat consumption:

- f. transferring the cooled gas from the heat consumption system to the high-temperature heat storage by means of the closed gas circuit as the heat transfer mechanism;
- 20 g. obtaining stored thermal energy from the high-temperature heat storage with the bulk refractory material (1) comprised in the high-temperature storage space (14) to form a hot gas;
- 25 h. transferring the hot gas from the high-temperature heat storage to the heat consumption system by means of the closed gas circuit as the heat transfer mechanism; and

- i. consuming the stored thermal energy from the hot gas in at least one heat consumption system;

characterized in that the bulk refractory material (1) comprises a particle fraction having a sphericity in the range of 0.4 to 1 and a mean particle size in the range of 0.5 to 20 mm, wherein the ratio of the volume of the largest to the smallest particles is at most 5:1,

wherein in steps d. and f., heat loss, escaping from the high-temperature heat storage due to heat transfer through the load-bearing inner shell (3) surrounding the high-temperature heat storage, is recovered by conducting the cooled gas through the gas gap (4.1) arranged between the load-bearing inner shell (3) and the thermal-insulating outer shell (5) surrounding the load-bearing inner shell (3).