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sandTES – An active thermal energy storage system based on the fluidization of powders

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Abstract

An active fluidization thermal energy storage (TES) called “sandTES” is presented. System design, the fundamental features and challenges of fluidization stability such as mass flux uniformity, powder transport and heat transfer, as well as auxiliary power minimization are thoroughly discussed. The tools and methods for evaluating or simulating the behavior of the fluidized bed heat exchanger (HEX) and the dense particle flow within it are explained along with criteria for the selection of storage powders.

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1. Introduction

Large scale thermal energy storage (TES) can deliver valuable contributions for balancing the volatile supply of renewable energy (electricity) with demand. TES can be well implemented in concentrating solar power (CSP) plants, thus offering a value increase in comparison to renewable energy from PV or wind. Even in conventional thermal power plants, TES can deliver solutions for increased flexibility.

For large scale TES the price of the storage material itself exhibits the major part of the investment costs thus making its selection a crucial one. Many solid powders are low cost products and well suited storage materials: They

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offer good values of thermal capacities (product of $\rho \cdot c_p$) and are easy to handle or transport. Their melting point is far above industrial interest making them applicable in the full temperature range of industrial interest.

In the sandTES concept, a storage concept currently under development at the Technical University of Vienna, powders are used as storage material in an active TES concept. In active TES concepts the primary heat transfer medium (HTF) and the storage medium are transported through a heat exchanger (HEX). This enables a steady state operation, high efficiency and design flexibility (almost unlimited range in the ratio power/energy). The sandTES concept applies fluidization technology to transport powders through a HEX in stationary fluidization regime.

In this work the sandTES concept is presented, the working principle and the overall design of the sandTES fluidized bed HEX is discussed. An idea for modeling is provided for better illustration of the potential of the sandTES concept. As storage material, only sand has been investigated in detail so far, but there are some promising alternatives to sand also being presented in this work.

Nomenclature

| | |
|---------------|--|
| A | area [m ²] |
| \dot{m} | mass flow rate [kg/s] |
| G | mass flux density [kg/m ² /s] |
| u | velocity [m/s] |
| t | factor [-] |
| ρ | density [kg/m ³] |
| c_p | heat capacity [kJ/kg/K] |
| ε | thermal capacity |
| CFD | computational fluid dynamics |
| CPFD | computational particle fluid dynamics |

Subscripts

| | |
|------|-----------------------|
| HEX | heat exchanger |
| base | Base of fluidized HEX |
| mf | minimum fluidization |

2. sandTES – active fluidization energy storage

The sandTES concept consists of a stationary fluidized bed with an internal tube bundle HEX, two solid powder hoppers and auxiliary devices handling the storage powder (conveyors) and blowers delivering the air enabling the fluidization.

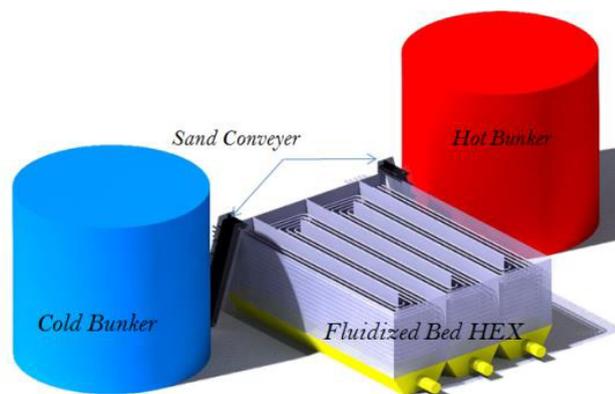


Figure 1: sandTES concept

2.1. Fluidization technique / sandTES fluidized bed HEX

Fluidization is a technique in which a stream of a gas (or a liquid) flows upwards through a bed of particles at a velocity being large enough to loosen and lift the particles. The onset of fluidization is characterized by the minimum fluidization velocity above which the particles of a bulk start to move within a restricted range and are suspended in the fluid percolating the bed. As the name already suggests, a fluidized bed behaves similar to a fluid.

The minimum fluidization velocity u_{mf} can be defined by a simple force balance: the total forces exerted by the fluid to the solid bulk have to be equal to the mass of all particles the bulk consists of, corrected by the buoyancy force. For practical application, semi-empiric correlations are available for evaluating the minimum fluidization velocity; the most prominent one is the correlation suggested by Wen and Yu [2].

In the sandTES fluidized bed HEX, air is entering through the distributor floor and so enabling the fluidization of the storage powder traveling through the HEX. Within the stationary fluidized bed, the inner walls can be arranged in a way allowing the powder to pass in serpentine through the HEX.

A tube bundle heat exchanger is arranged in a way it allows a counter-current flow heat exchange between the powder and the primary heat transfer fluid (HTF). The blowers needed for fluidization represent an auxiliary power which needs to be minimized. For minimizing blower power the fluidization air mass flow has to be optimized:

$$\dot{m}_{air} = A_{base}(t_{mf}u_{mf})\rho \quad (1)$$

In the mass balance of the distributor floor (Eq. 1) it can be seen that the overall dimensions of the fluidized bed HEX and the fluidization air velocity (written as a multiple of u_{mf}) influence blower power. As a clear consequence, the sandTES fluidized bed HEX should be operated as close as possible to the minimum fluidization condition ($t_{mf} \sim 3 - 5$), but nevertheless a stable fluidization thus powder transport has to be guaranteed.

The minimum fluidization velocity u_{mf} is dependent on the particle diameter d_p by the power of approximately 1 (between 0.8 and 1.8). The smaller the particles of the powder are, the less air is needed for fluidization. On the other hand, at least in the case of sand, finer particle size requires sieving and results in higher cost.

Fine powders do not only need less air for fluidization, they also offer higher heat transfer coefficients. In Fig. 2a the heat transfer coefficients for silica sand are shown and in Fig. 2b the dependency of the minimum fluidization velocity on the particle size.

An economic optimum between the size and the price of the powder has to be found when designing a sandTES system.

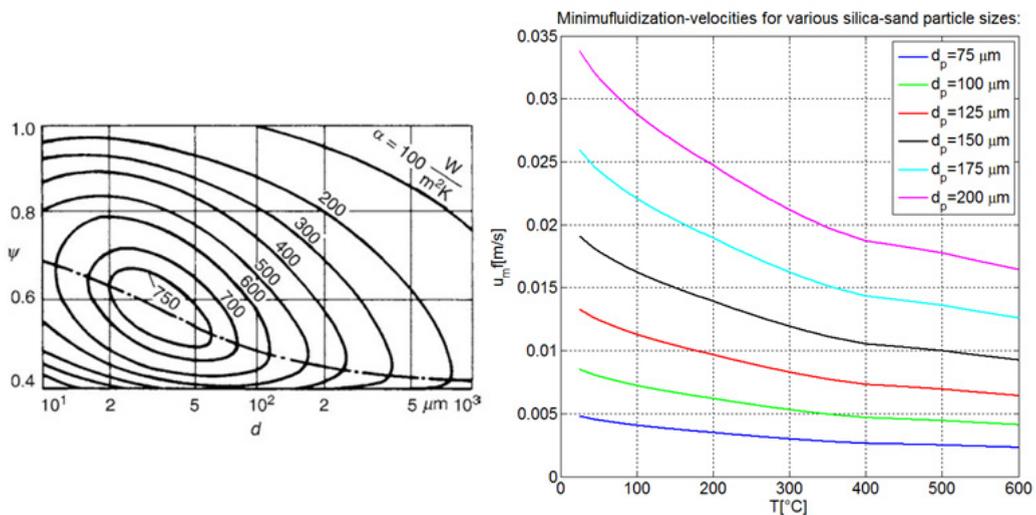


Figure 2: (a) heat transfer coefficient of a fluidized bed (silica sand) [1], (b) minimum fluidization velocity for various silica-sand particle sizes (based on the Wen & Yu correlation)

2.2. sandTES active fluidization concept

The particle suspension of the storage powder is flowing freely through the HEX via fluidization technique. The storage powder is collected in an adequate cold and hot hopper, where it is transported to and from via an appropriate conveyor (e.g.: bucket chain conveyor).

In charge mode, the storage powder is transported via a conveyor from the cold hopper to the fluidized bed HEX and entering it on the left-hand side; the cold end (Fig. 1). The storage powder is heated up while flowing through the HEX, as the hotter primary HTF travels in a counter-current flow through the inner tube bundle. The hot primary HTF is entering the sandTES-HEX on the right-hand side; the hot end. The hot storage powder is transported again via a conveyor to the hot hopper, where it is collected.

In discharge mode, both flow directions, the one of the primary HTF and the one of the storage powder, are reversed. So the hot end stays the hot end as does the cold one. This minimizes losses during switching between charge and discharge mode, what is especially important since a significant amount of the storage powder stays within the fluidized bed HEX as a bulk (without fluidization) in idle periods. The sandTES-fluidized bed HEX stays in a hot stand-by mode in idle periods enabling fast start-ups/sudden load variations.

As the sandTES-concept is an active TES, it offers over the entire operation period steady state behavior and flexible part load performance; since both the mass flow of the primary HTF and of the storage powder can be adjusted.

2.3. Broad field of applications of non pressurized storage

Since the sandTES-concept applies a tube bundle HEX, the primary HTF passes through, the sandTES concept can be applied in many types of applications. The most promising large scale applications are load dispatching in thermal or solar thermal power plants [5] and thermodynamic electricity storage such as Adiabatic Compressed Air Energy Storage [3, 4].

2.4. Recuperation of fluidization Air

The temperature of the fluidization airs exiting the HEX is in practical terms equal to the local powder temperature (the heat transfer area between air and all particles is immense). If the blowers are fed with cold air, it will be heated up the bed's temperature by travelling through the bed. Not recuperating the hot air will account for a significant loss; thus recuperation of the fluidisation air with plate HEX is important for minimizing thermal losses, especially at the hot end of the sandTES fluidized bed HEX. Up to temperatures around 400°C, the fluidization air can alternatively be re-circulated via hot going blowers.

2.5. Filtering of the exhaust Air

For an efficient function of the sandTES concept, medium-fine to fine powders are applied which could cause health issues when inhaled in large quantities (respirable dust). The fine particles are therefore removed from the exhaust air in baghouse filters.

In the following section an idea of modeling and the needed tools are provided, before some specific design challenges will be discussed.

3. Modeling the fluidized bed HEX

Depending on the application, a single sandTES fluidized bed HEX has to handle a temperature range of up to 650 °C. As pointed out in the paragraphs before, the stationary fluidized bed should be operated as close to the minimum fluidization condition as a stable fluidization can be ensured. Since thermodynamic properties are by nature temperature dependent, it is crucial to know the local behavior of the fluidization in the HEX in order to optimize the concept.

For an efficient HEX operation the heat capacity streams of both the primary HTF and the storage powder have to be equal. Since they are also temperature dependent, the knowledge of the local heat capacity streams is necessary for increasing the efficiency (determining the minimum needed HEX-surface area).

Computational Fluid Dynamics (CFD) for dense particle flows is numerically far too expensive for investigating an entire sandTES fluidized bed HEX. A model based on Heat Exchanger Networks has been developed to analyze the HEX on the macro scale.

Nevertheless also the flow behavior has to be looked into in detail. This makes reliable CFD-simulations and experiments necessary. A code specialized on dense phase particle flows was chosen, being at the moment of writing the only one capable of calculating such particle flows feasibly : Barracuda®.

3.1. Macro scale (heat exchanger network – self developed code)

The entire HEX is subdivided into sub heat exchangers. For each sub-HEX, a specific HEX-design can be applied (e.g.: counter-current, shell-and-tube, one-sided stirred tank...). The thermodynamic properties of each sub-HEX are evaluated so that the classical HEX-behavior or interaction of the two involved heat capacity streams can be investigated. They are on average equal but do differ locally significantly causing a non linear course of the temperature changes over the HEX.

From the fluidization point of view the distributor floor is subdivided into (and fed by) various wind boxes to ensure a local stable fluidization near the minimum fluidization condition. A special nozzle/distributor floor has been developed which is also modeled in detail. This nozzle/distributor floor guarantees a stable fluidization despite large local disturbances. Due to the enormous importance of the nozzle/distributor floor, this model has also been validated experimentally. Overall global and local energy & mass balances are calculated in our self developed tool which allows investigating all applications of the sandTES-concept.

3.2. Micro scale (CPFD - Simulations)

The particle flow cannot be analyzed on the macro scale. For investigating the particle flow, the commercial simulation code Barracuda® has been chosen. Particle flow simulation requires a multi-physics approach, since the air flow is calculated best with on an Euler grid, whereas the particles' physics are described best via a Lagrange approach. Barracuda® applies the Multiphase Particle-in-Cell Method (MP-PIC) [6], combining both the Euler and Lagrange description in one code being at the moment of writing the only program capable of simulating dense particle flows at a convenient calculation expense; CPU-time still has to be estimated in the magnitude order of weeks.

4. Fluidization Challenges

4.1. Backpressure

The particle suspension of storage powder (fluidized bed) is flowing through the HEX. Since there is some flow resistance, backpressure is occurring, resulting in height differences of the fluidized bed (... imagine honey flowing through the HEX). This is a challenge for the nozzle/distributor floor, because the pressure difference of the windbox pressure and the pressure above the fluidized bed is constant over one windbox-section. The pressure loss of the gas enabling the fluidization is direct proportional to the height/level of the fluidized bed. When operating the HEX near the minimum fluidization conditions while having significant height differences of the bed over one windbox section, the following worst case scenario could occur:

The major part of the air from the windbox would flow through the bed at the side of the windbox section where the bed level is the lowest. At the other end of the bed there would not remain enough air mass flow for fluidization. The bed would collapse at the end where the bed is higher.

A special nozzle/floor has been developed prevent such a scenario.

4.2. Powder mass flow distribution/design of the tube bundle

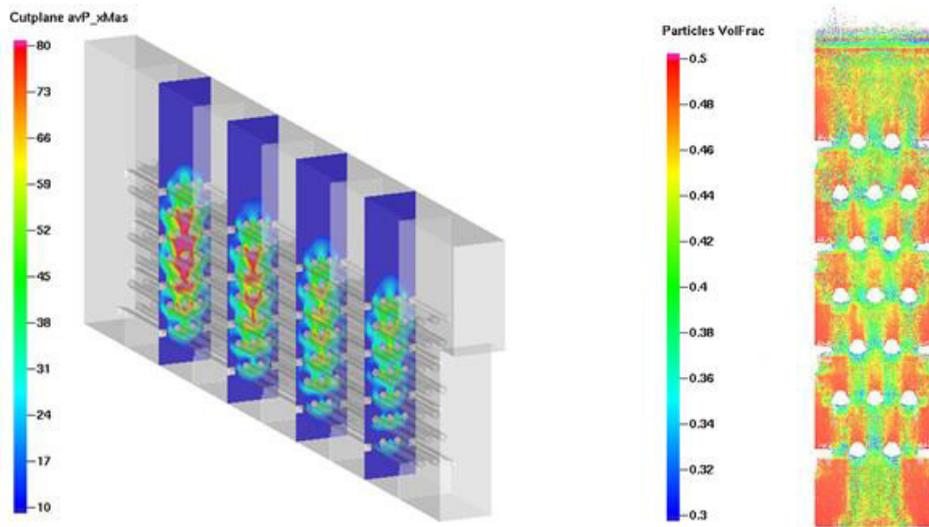


Figure 3: Barracuda Simulations: left-hand side: axial mass flux of the powder through a HEX, right-hand side particle volume fraction in between a tube bundle

For an efficient sandTES fluidized bed HEX, not only the auxiliary power has to be minimized, it has also to be ensured that the entire tube bundle is used efficiently or in other words is being wetted by the powder mass flow. The axial powder flow rate should be equally distributed over the height of the tube bundle, such that each pipe can exchange the same amount of heat.

Simulations (Fig. 3) proof that a staggered arrangement of the tube bundle is better than an in-line arrangement. In a staggered design with a horizontal pitch twice the outer diameter of a pipe, there is no direct vertical path for the fluidization gas from the distributor floor to the surface of the fluidized bed. Thus the fluidization gas has to pass in a zig-zag-pattern around the pipes of the tube bundle enabling a far more homogeneous fluidization between the pipes of the tube bundle than in an in-line arrangement.

For influencing the axial powder mass flow distribution over the height, vertical baffles are introduced in regular distances, in order to force the powder back in between the tube bundle area. The price to pay is the more the powder mass flow is directed by baffles (the deeper a baffle is introduced into the tube bundle), the higher the resistance for solids flow will be. Height differences of the fluidized bed before and after a baffle are induced.

4.3. Flow rates/design of the tube bundle

For minimizing the power of fluidization air blowers, it is also important to minimize the volume of the fluidized bed (not only the base area of the HEX as mentioned above): The lower boundary condition is that the powder needs to have sufficient space to flow freely through the HEX.

For an efficient HEX operation, the heat capacity flows of the primary HTF and of the storage powder have to be (on average) equal. The flow rate of the primary HTF flowing through the pipe is coupled to the flow rate of the storage powder and they cannot be chosen independently. As explained in the paragraph before, for a homogeneous fluidization the horizontal pitch should be twice the outer pipe diameter; thus the only remaining degree of freedom is the vertical pitch. Assuming that the vertical pitch should not be larger than 4-5 times the outer pipe diameter, the bottleneck for the mass flow rates is the powder mass flux density, especially in case of primary HTFs having a higher thermal density.

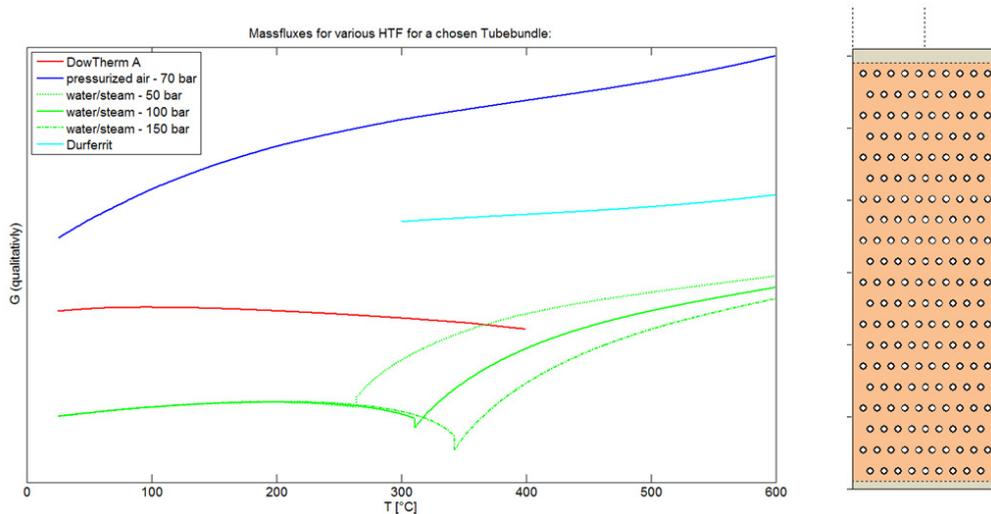


Figure 4: Maximum mass flux densities G for various HTFs for a given tube bundle (qualitatively)

For a given tube bundle, the maximum average powder mass flux density can be evaluated via Barracuda® Simulations. The maximum heat capacity flow rate a HEX can handle can be deduced in consequence. With the fixed heat capacity flow also the maximum mass flux densities for any primary HTF can be determined.

In Fig. 4 the feasible maximum mass flux densities G for a variety of different HTF are shown on a qualitative basis, for a silica sand powder and a given bundle geometry.

5. Storage media

In the development process of the sandTES-concept, silica sand (SiO_2) has been contemplated as storage powder. Silica sand is an abundantly available natural product and has a convenient thermal capacity. Furthermore silica sand is offered in many grain sizes and intervals. In fluidization technology sand is commonly used, since it is a stable and inert material. Most correlations needed in fluidization engineering are valid for sand.

5.1. Criteria for the storage media selection

In favor of small storage volumes, the thermal capacity $\varepsilon = \rho c_p$ of the storage powder should be as large as possible. From the viewpoint of fluidization technology, materials of higher density are punished; since the minimum fluidization velocity u_{mf} is the higher the denser a material is (*ceteris paribus*). But as already explained in section 2.1, u_{mf} is also dependent on the particle diameter. Thus it is thinkable to compensate a higher particle density with a smaller particle diameter when u_{mf} is kept constant over a variation of materials.

5.2. Geldart classification

If particles are too small, they cannot be fluidized easily any more. Geldart [7] suggested a classification schema on a material's fluidization behavior being dependent on the particle diameter and on the material's density. In the Geldart's diagram (Fig. 5) particles are classified in 4 types: A-aeratable, B-sand like, C-cohesive and D-spoutable. For easy and stable fluidization, particles of well suited storage powder should be around the boundary line between type A and type B powders. In Table 1 various potential storage materials are presented. Since for fluidization a higher heat capacity is more favorable than a higher density, we plotted in Fig. 6 on the right-hand side the thermal capacity over material density. The closer a material is to the upper left corner, the better it is suited for the sandTES concept.

In Fig. 6 on the left-hand side, each material is shown with 4-diameters ($d_p=50, 100, 150, 200[\mu\text{m}]$) in the Geldart diagram. The closer a particle is to the green line, the better it is suited for the sandTES-concept.

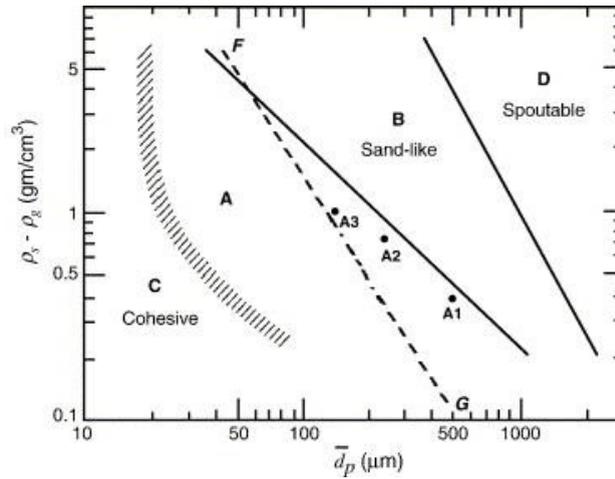


Figure 5: Geldart Diagram [7]

Table 1: potential storage media [7]

| | c_{pm} [J/kgK] | ρ [t/m ³] | $\varepsilon = \rho c_p$ [J/cm ³ K] | U_{mf50} [mm/s] 50 μ m | U_{mf100} [mm/s] 100 μ m | U_{mf150} [mm/s] 150 μ m |
|--|---------------------|-------------------------------|---|------------------------------------|--------------------------------------|--------------------------------------|
| Quartz SiO₂ | 742.13 | 2.65 | 1.97 | 2.5 | 8.5 | 17.2 |
| Feldspar: | | | | | | |
| Albite NaAlSi ₃ O ₈ | 782.16 | 2.62 | 2.05 | 2.4 | 8.5 | 17.0 |
| Microcline KAlSi ₃ O ₈ | 727.19 | 2.56 | 1.86 | 2.4 | 8.3 | 16.6 |
| Anorthite CaAl ₂ Si ₂ O ₈ | 759.85 | 2.76 | 2.10 | 2.6 | 8.9 | 17.9 |
| Mica: | | | | | | |
| Muscovite KAl ₂ (AlSi ₃ O ₁₀)(F,OH) ₂ | 818.71 | 2.83 | 2.32 | 2.6 | 9.1 | 18.4 |
| Fluorophlogopite KMg ₃ AlSi ₃ O ₁₀ F ₂ | 812.83 | 2.88 | 2.34 | 2.7 | 9.2 | 18.7 |
| Pyroxene: | | | | | | |
| Jadeite NaAl(SiO ₃) ₂ | 791.29 | 3.35 | 2.65 | 3.1 | 10.6 | 21.8 |
| Diopside CaMg(SiO ₃) ₂ | 768.96 | 3.28 | 2.52 | 3.0 | 10.4 | 21.3 |
| α -Spodumene α -LiAlSi ₂ O ₆ | 853.89 | 3.19 | 2.72 | 2.9 | 10.2 | 20.7 |
| β -Spodumene β -LiAlSi ₂ O ₆ | 874.85 | 2.38 | 2.08 | 2.2 | 7.7 | 15.5 |
| Iron Ores: | | | | | | |
| Hematite Fe ₂ O ₃ | 650.31 | 5.28 | 3.43 | 4.7 | 16.3 | 34.2 |
| Magnetite Fe ₃ O ₄ | 651.25 | 5.20 | 3.39 | 4.6 | 16.0 | 33.8 |
| Slags: | | | | | | |
| Aluminium Oxide Al ₂ O ₃ | 761.05 | 3.97 | 3.02 | 3.6 | 12.5 | 25.8 |
| Magnesium Oxide MgO | 923.36 | 3.58 | 3.31 | 3.3 | 11.3 | 23.3 |
| Manganese Oxide MnO | 621.75 | 5.37 | 3.34 | 4.7 | 16.5 | 34.8 |
| Titanium Dioxide TiO ₂ | 687.73 | 4.23 | 2.91 | 3.8 | 13.2 | 27.5 |

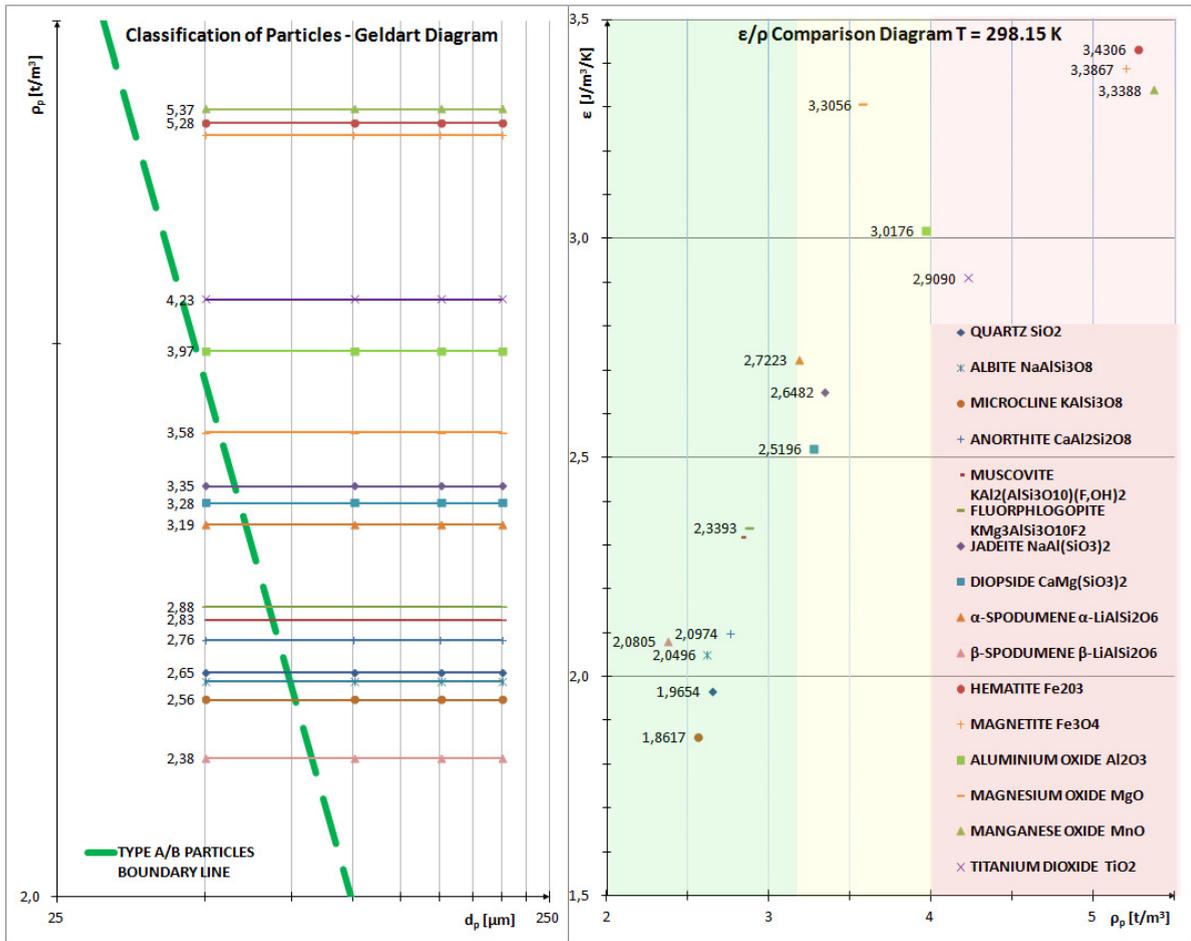


Figure 6: (a) potential storage media shown in the Geldart diagram, (b) their thermal capacity plotted over density

5.3. Artificial material/sintered materials

A very interesting and promising storage material is an easy to fluidize powder of sintered materials; like crushed fire bricks, or a powder of heat resistant coatings. These products are mainly made out of Aluminium Oxid Al₂O₃ (2/3) and Magnesium Oxid MnO (1/3). Both materials have high values of heat capacity and are very dense. For minimizing the blower power of the sandTES-concept, it can be advantageous if the density of a particle can be reduced; since less air is needed for enabling the fluidization. Sintered particles would be particles with a reduced density. It has to be investigated if the potential reduction of blower power is not out weighted by the decrease in thermal capacity; thus larger storage volumes. But nevertheless the porosity would deliver another degree of freedom for designing a sandTES system. Furthermore material costs of artificial storage powders will be generally speaking higher than natural products.

6. Conclusion

The sandTES-concept has been presented and its capability of using low cost powders as storage materials in an active concept. It has been shown how the auxiliary power needed for enabling the fluidization/storage powder transport through the fluidized bed HEX can be minimized. The challenges in designing a sandTES-HEX ensuring a stable and efficient operating behavior have been discussed and potential well suited storage materials have been presented.

Acknowledgements

Investigating a new storage concept, in times where R&D budgets are small, is not possible without a motivated team, overcoming the economic limitations via extraordinary engagement and smart ideas. We want to express our warm appreciation to everyone involved in the sandTES project at the Technical University of Vienna, especially the master and bachelor students doing the experimental work.

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