Aerogels - Production, Properties and Applications

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Abstract

Aerogels are highly porous sol-gel derived solids. Their properties, which are extremely fascinating as well as very promising for a large number of applications, are due to their nanostructure. Aerogels can be produced from a variety of materials, whereby silica aerogels are the most thoroughly studied ones. Silica aerogels with densities ranging from a few kg/m$^3$ to a few hundred kg/m$^3$ have been made as monoliths, in granular form or as powders.

This paper describes the fundamentals of the sol-gel process, drying techniques and the basic aerogel properties. Special attention is given to their nanostructure and the resultant very low thermal conductivity. Most of the applications so far are based on the thermal, mechanical and optical properties of silica aerogels which are described.

1. History

Aerogels are highly porous sol-gel derived materials. The key to their production was found in 1931, when S.S. Kistler discovered a procedure to remove the liquid from a wet gel without causing shrinkage of the gel. Up to then, the drying of a gel, still embedded in the solvent consisting mainly of alcohol with some water and catalyst, was performed by evaporation of the liquid in air. The occurring liquid-vapor interfaces within the gel network result in capillary tensions that cause considerable shrinkage of the gel due to a partial collapse of the network. The shrinkage continues until the gel structure is strong enough to withstand these forces. The resultant “xerogels” have a remaining porosity of about 50%.

To avoid shrinkage of the gel, the build-up of capillary forces has to be prevented. Kistler’s idea was to “replace the liquid with air by some means in which the surface of the liquid is never permitted to recede within the gel”. He was the first to apply “supercritical drying”: The aerogel is put in a pressure vessel, an autoclave. Then, the temperature and the pressure are raised above the critical point of the solvent. Since in a supercritical fluid, the liquid and vapor phases become indistinguishable, no capillary forces occur. After releasing the fluid through the outlet valve and subsequent cooling, an aerogel is obtained. Kistler produced SiO$_2$-Aerogels with densities between 20 and 100 kg/m$^3$, as well as aerogels of aluminium, ferric, stannic oxides and other materials. Kistler’s original method was substantially improved by S.J. Teichner and his coworkers, who investigated the storage of oxygen and rocket propellants in porous materials.

A stimulating event was the application of aerogels in Cerenkov detectors in high-energy physics. Today, ultralow-density aerogels with densities as low as 3 kg/m$^3$ can be prepared.

This extremely high porosity in combination with structures in the nanometer region endows aerogels with fascinating properties.

2. Preparation

2.1 Sol-Gel Process

The sol-gel process is the transition of a system of colloidal particles dispersed in a solution into a branched, continuous network which is still embedded in the liquid. Kistler’s way to produce silica aerogels was the polycondensation of sodium silicates. Today, the most frequently used method to prepare monolithic aerogels is the hydrolysis and polycondensation of organometallic precursors such as tetramethoxysilane (TMOS). This method allows the convenient variation of reaction parameters. Up to now, aerogels of main group oxides, transition and semimetal oxides, as well as organic...
and carbon aerogels have been produced via the sol-gel route. Since silica aerogels are the most thoroughly studied ones, we mainly consider them in the following.

First, a liquid silicone alcoxide is hydrolysed by addition of water and a catalyst:

$$\text{Si(OR)}_4 + 4\text{H}_2\text{O} \rightarrow \text{Si(OH)}_4 + 4\text{ROH}$$

where R denotes an alkyl group. Then, the silicic acid condenses by expelling water:

$$2\text{Si(OH)}_4 \rightarrow (\text{OH})_2\text{Si}^{-}\text{O-Si(OH)}_2 + \text{H}_2\text{O}$$

In reality, both reactions proceed more or less simultaneously. Additional (≡Si-O-Si≡) linkages are produced by further polycondensation reactions until a tenuous network of SiO₂-tetrahedra exists. The structural growth process can be controlled by the reaction rates of hydrolysis and condensation.

Both reactions are catalysed by acids or bases and therefore exhibit a strong dependence on the pH-values. Hydrolysis, which is additionally influenced by the water-to-alcoxide ratio, shows a minimum of reaction rate at pH=7, which strongly increases for low and high pH-values. The condensation rate has a minimum at the isoelectric point of silica (pH≈2) but is large under neutral or basic conditions. Controlling the amount of catalyst and the temperature, either polymer-like silica chains (under acidic conditions) or comparatively dense, colloidal particles (basic conditions) are obtained. These substructures then aggregate to clusters, which finally build up the gel network (Figure 2). The aggregation rate is additionally influenced by the degree of dilution (i.e. the amount of excess alcohol) and is responsible for the final density of the gel. The gel point is reached when a cluster has formed which spans the sample vessel.

Hereafter, during the “aging” phase, the condensation reactions continue and remaining small clusters or sol particles attach to the existing network. Depending on the aging conditions, additional strengthening of the network by dissolution and precipitation, or shrinkage (syneresis) and the expulsion of water may occur.

The sol-gel process allows tailoring nanostructured materials by providing the appropriate reaction parameters. Furthermore, it permits the production of homogeneous multicomponent materials in a controlled fashion.

### 2.2 Drying

As already mentioned above, the crucial point is to avoid the irreversible collapse of the gel structure. The usual way of doing this is the application of supercritical drying. Therefore, the gel, together with a sufficient amount of solution (e.g. methanol), is placed in a pressure vessel and heated until temperature and pressure have reached the critical point of the solvent. The gel is then immersed in a...
supercritical fluid which can then be gently blown off. After cooling to ambient conditions, the vessel can be opened.

Two different modifications of the supercritical drying process are usually applied. In the so-called hot-drying process, it is performed with respect to an organic liquid (e.g. methanol or aceton). This requires temperatures of about 250°C and pressures of about 80 bar. Since the handling of pressurized, flammable liquids is not without risks, a "cold"-drying procedure can be employed as an alternative. Here, the pore liquid is exchanged for a non-flammable liquid with low critical temperature (e.g. carbon dioxide). This is achieved by pressurizing the autoclave with liquid carbon dioxide (typically at 10°C). The gel is then rinsed until all original pore liquid is exchanged. A disadvantage of this method is that a complete solvent exchange may take a considerable time, depending on sample size and pore size distribution.

A different approach to extracting the solvent is subcritical drying. During subcritical drying, menisci develop and thus capillary forces occur (Figure 1). The forces increase with decreasing pore width and increasing surface tensions of the solvent. To minimize the gel shrinkage, washing steps are performed to eliminate the smallest pores and to strengthen the network and/or to achieve a chemical modification of the inner surface, e.g. by silylation. These silyl-modified gels contract in the expected way as capillary forces develop. However, when the liquid phase starts to form isolated droplets and surface tension ceases, a "springback" effect is observed: Since neighbouring surface sily groups are chemically inert and can detach with little activation energy, the gel body is able to re-expand.

An advantage of subcritical drying is that the aerogel production can be performed without an autoclave.

2.3 Modifications
CO₂-dried silica aerogels have a large number of OH groups on their inner surface, which typically measures some hundred m²/g. For that reason, they are hydrophilic and fracture into submicron-sized SiO₂ clusters if they come in contact with liquids. The same holds for alcohol-dried samples, which are first hydrophobic due to the substitution of OH by OR-groups during the autoclave process. However, during storage, re-substitution takes place induced by ambient moisture. In terms of disposal this might be advantageous, but for handling and storage reasons, hydrophobic aerogels are preferred. Such aerogels can be made by adding about 20% of methyltrimethoxysilane to the starting precursor. These aerogels float on water for months without uptake of liquid. Subcritically dried silylated aerogels are also hydrophobic.

Another important modification of silica aerogels is the enhancement of their IR-extinction and thus the reduction of radiative heat transfer by adding IR-opacifiers, e.g. carbon black. The opacification can be achieved either by adding finely dispersed carbon black particles to the sol-gel solution or by pyrolysis of organic groups which are integrated in the inorganic SiO₂ network.

Very exciting is the modification of resorcinol formaldehyde (RF) aerogels. If pyrolysed at about 1000°C, they are transformed into highly porous electrically conductive carbon aerogels.

3. Characterization and Physical Properties

3.1 Structural Investigations
Many methods have been used to investigate the structure of aerogels. By using the NMR technique, the extent and kinetics of hydrolysis and condensation during gelation can be studied. Thermoporometry can be used to determine the pore size distribution of the wet gel. Nitrogen sorption measurements have been used to determine the specific surface area. However, since only pores up to about 50 nm are detected, the determined pore volumes are much lower than the expected values, especially for densities below 200 kg/m³. Furthermore, the condensation and surface tension of LN₂ has been shown to destructively change the structure and the mesopore size distribution.

Helium pycnometry is used to determine the skeletal volume and thus the skeletal density of silica aerogels. The skeletal densities were found in the range of 1700 to 2100 kg/m³. This would correspond to a porosity of the aerogel backbone in the order of 5% to 20%, but it could also be explained by different bond lengths compared to vitreous silica.

Mercury porometry to determine the pore volume cannot be applied to aerogels. Due to the surface tension of Hg and the low compressive modulus of aerogels, only compression of the tenuous body as a whole occurs instead of penetration.

Additionally, TEM studies have been performed. This method might cause destruction (sintering) of
3.2 Small Angle X-Ray Scattering (SAXS)

The most powerful and reliable methods to probe aerogel structures are scattering techniques. The sample is irradiated by particles (neutrons) or photons (light, X-rays) and the characteristics of the detected scattering pattern can be related to structural features. The typical arrangement of a scattering experiment is shown in Figure 3. In the case of x-ray scattering, the amount of scattered intensity is due to inhomogeneities in the electron (or nucleon) density of the porous body. For a statistically isotropic structure, the scattered intensity depends solely on the absolute value of the scattering vector $q = (4\pi / \lambda) \sin (\theta / 2)$, where $\theta$ denotes the scattering angle and $\lambda$ the wavelength.

Since the structures in real space and the scattered intensity observed in q-space are connected by a Fourier transformation, a reciprocal behaviour is observed: large structural features appear at small q values and vice versa. With expected structural sizes of 1 to 100 nm and typical x-ray wavelengths of 1 to 2 Å, the scattering intensities have to be detected at small scattering angles (0.01° to 10°), i.e. close to the primary beam. This is why the technique is called small-angle x-ray scattering.

A typical scattering curve of an aerogel consisting of a particle network is shown in Figure 4. The characteristics of the scattering pattern can be related to the different structural features on the respective length scales. At smallest scattering vectors, which correspond to a length scale much larger than the inhomogeneities, a constant scattering intensity is observed. With increasing q, a length scale is reached where the largest inhomogeneities (pores or clusters of size R) are resolved. Subsequently, a more or less extended linear decay is observed in the double-logarithmic plot. This is due to the branched appearance of the gel and may be explained by a fractal network. The intensity drops as $I \propto q^{-D_s}$, where the exponent $D_s$ is called the mass fractal dimension. A second crossover is observed at $q \approx 1/r$, when the scale approaches the particle size $r$. Upon further increase of the scattering vector, the scattering becomes sensitive to the nature of the particle surface. Again, a power-law behaviour is observed: $I \propto q^{-D_s'}$, where $D_s'$ is called the surface fractal dimension. Smooth surfaces with $D_s = 2$ lead to a decay proportional to $q^{-4}$; this is called Porod's law. In this case, the specific surface area and the skeletal density can be calculated. Fractally rough surfaces cause a less steep decay with $D_s = 2 - 3$. A further increase of q resolves the structures on the molecular scale, where broadened Bragg peaks due to the partially ordered substructure are observed.

X-ray scattering curves of three different TMOS silica aerogels, catalysed at pH = 9, 11 and 13 are shown in Figure 5. All specimens had similar macroscopic densities ($\rho \approx 230$ kg/m³). The scattering vector q, at which the scattering intensities become independent of q, is shifted to lower values for decreasing pH-values. This corresponds to an increasing cluster size R (from about 8 to 15 nm) with decreasing pH-values. Similarly, the particle radii $r$ obtained from these scattering curves increase from approximately 1 to 3 nm. For a comparison, we have included the x-ray scattering intensity of a fumed silica powder in Figure 5. The fumed silica powder has been pressed to a tablet with a density of 300 kg/m³, which is comparable to the density of the presented aerogel samples. The fumed silica also shows a fractal network structure.
consisting of smooth primary particles of about 10 nm (crossover at \( q = 0.3 \text{ nm}^{-1} \)), which is about a factor of 10 larger than in the presented aerogels. The cluster size of the fumed silica could not be determined as the scattering curve still increases even at the smallest scattering vectors available. An extension of the measurement range is possible by using ultra small-angle x-ray scattering (USAXS)\textsuperscript{26}.

3.3 Optical and Infrared-Optical Properties

Silica aerogels are, if properly made, highly transparent in the visible spectral region\textsuperscript{27}. At 630 nm, the specific extinction coefficient \( \epsilon_{\text{vis}} \) is in the order of 0.1 \( \text{m}^2/\text{kg} \).\textsuperscript{28} For an aerogel with a density of \( \rho = 100 \text{ kg/m}^3 \), this corresponds to a photon mean free path of \( l_{\text{ph}} = 1/(\epsilon_{\text{vis}} \cdot \rho) \approx 0.1 \text{ m} \) at 630 nm. Due to the pore structures in the order of 1 to 100 nm, strong Rayleigh scattering is observed within the blue and ultraviolet spectral region. This leads to a bluish appearance of aerogels if viewed against a dark background. The extraction of particle diameters from optical transmission measurements is non-trivial since multiple scattering has to be taken into account.

In the infrared region, silica aerogels show besides the absorptions bands of SiO\textsubscript{2}, additional strong absorption of water, which is chemi-or physisorbed on the huge inner surface. Specific extinction spectra for aerogels with varying water content are shown in Figure 6. Typically, the specific extinction is smaller than 10 \( \text{m}^2/\text{kg} \) for wavelengths below 7 \( \mu \text{m} \) and above 30 \( \mu \text{m} \). Between 7 \( \mu \text{m} \) and 25 \( \mu \text{m} \), a specific extinction above 100 \( \text{m}^2/\text{kg} \) is observed. Compared with the specific extinction in the visible region, a ratio of \( \epsilon_{\text{IR}}/\epsilon_{\text{vis}} > 100 \) is obtained. Thus, silica aerogels can be considered as transparent insulating materials that efficiently transmit solar light, but strongly block 300 K thermal infrared radiation. Integration of carbon black into the aerogel increases its IR-extinction dramatically, however, it also renders the material opaque in the visible.

Typical SiO\textsubscript{2}-aerogels show practically no refraction and no reflection, which is due to the fact that about 99\% of their volume is air. For low-density aerogels, the correlation between the index of refraction \( n \) and the density \( \rho \) is \( n = 1 - 2.1 \cdot 10^{-4} \rho/\text{kg} \cdot \text{m}^3 \),\textsuperscript{29} thus for \( \rho \approx 100 \text{ kg} \cdot \text{m}^3 \), one expects \( n \approx 1.02 \).

3.4 Thermal Properties

The thermal transport in pure and opacified aerogels has been studied extensively. In principle, all three heat transfer mechanisms, i.e. gaseous and solid conduction as well as radiative transport, occur\textsuperscript{30}. Additionally, various coupling phenomena between these heat transfer modes have been investigated\textsuperscript{31,32}.

3.4.1 Monolithic Aerogels

Due to aerogel pore sizes in the order of 50 to 100 nm and a mean free path of air at 1 bar of 70 \( \mu \text{m} \), the gaseous heat conduction is partially suppressed. Evacuation to about 20 mbar is sufficient to fully eliminate gaseous conduction.

Solid conductivity \( \lambda_s \) is drastically reduced with respect to vitreous silica and has been found to scale with the density \( \rho \) according to\textsuperscript{33,34}:
\[ \lambda_s \propto \rho^\gamma, \] with \( \gamma \approx 1.2 \ldots 1.8 \)

\( \lambda_s \) also depends on the connectivity of the network and can thus be influenced by the preparation conditions.

The radiative heat transfer in aerogels is governed by their infrared absorption (see Figure 6). At ambient and elevated temperatures, a significant part of the thermal radiation is transmitted through the aerogel due to its relatively low specific extinction below 7 \( \mu m \). As mentioned above, the radiative heat transfer can be reduced drastically if an opacifier (e.g., carbon black) is added to the silica sol and thus integrated into the gel. As can be seen in Figure 6, the specific extinction is strongly increased, especially below 7 \( \mu m \). The radiative heat transfer in opacified aerogels can be regarded as a diffusion phenomenon. The radiative conductivity \( \lambda_r \) in this case is given by:

\[ \lambda_r = \frac{16 \sigma \cdot n^2 \cdot T^3}{3 \cdot E}, \]

where \( T \) is the absolute temperature, \( n \) the index of refraction, \( \sigma \) the Stefan-Boltzmann constant and \( E \) the infrared extinction, which is related to the specific extinction \( E\text{\textsubscript{w}} = E/\rho \). For \( \rho = 100 \text{ kg/m}^3 \) and \( E\text{\textsubscript{w}} = 100 \text{ m}^2/\text{kg} \), one obtains \( E = 10^4 \text{ m}^{-1} \) which corresponds to a photon mean free path \( 1/E \) of \( 10^{-4} \text{ m} \). Opacified aerogels with a thickness of about 0.01 m can then be considered as being optically thick. The resultant radiative conductivity at 300 K is only 0.001 W/(m·K).

The total thermal conductivity of an opacified monolithic SiO\textsubscript{2}-aerogel of density 120 kg/m\textsuperscript{3} is about 0.013 W/(m·K) at 300 K\textsuperscript{0}. The contribution of the solid conduction is about 0.005 W/(m·K) and of the gaseous conduction 0.007 W/(m·K).

### 3.4.2 Powdery and Granular Aerogels

In powdery aerogel, the network structure which is responsible for the solid heat conduction exists only within the grain boundaries. The thermal contact resistances between the grains then cause a reduction in solid conductivity of the aerogel powder to about \( \lambda_s = 0.001 \) to 0.002 W/(m·K), assuming an external load of 1 bar on the powder bed. On the other hand, due to the intergranular voids, the gaseous conductivity \( \lambda_g \) is considerably increased to about \( \lambda_g = 0.015 \) W/(m·K). To suppress gaseous thermal transport, powdery aerogel fills have to be evacuated below 1 mbar.

The radiative transfer depends on the grain/void sizes \( \phi_\rho \) and their ratio to the mean free path of the photons \( \lambda_{\text{ph}} \), which is in the order of \( 10^{-4} \) m for opacified aerogels. If \( \phi_\rho \ll \lambda_{\text{ph}} \), the photons "see" a homogeneous medium and are absorbed over small distances. In the case \( \phi_\rho \gg \lambda_{\text{ph}} \), the photons preferentially travel in the intergranular voids and the attenuation of the radiative flux is thus small.

The total thermal conductivity (Figure 7) of aerogel powders in air is below 0.02 W/(m·K) and can be as low as 0.003 W/(m·K) if they are evacuated. For granular aerogels, the measured conductivities are considerably higher.

### 3.5 Elastomechanical Properties

Due to the high porosity of the gels, the longitudinal sound velocity \( v_l \) can be as low as 20 m/s\textsuperscript{37} for a density of 5 kg/m\textsuperscript{3} (Figure 8). Young's modulus \( Y \) for such low density aerogels is in the order of \( 10^4 \text{ N/m}^2 \), i.e., about 6 orders of magnitude smaller than for vitreous silica. Generally, a scaling behaviour of \( v_l \) and \( Y \) with the aerogel density is observed.

![Fig. 7](image_url)

**Fig. 7** Thermal conductivities of granular and powdered silica aerogels laced with carbon black as a function of air pressure.

![Fig. 8](image_url)

**Fig. 8** Longitudinal sound velocity \( v_l \) of porous systems versus density. Vitreous silica (x) ; opal (○) ; aerogels for drying purposes (+) and silica aerogels of different density (ρ) produced at LLNL (Livermore) (▲) ; Airglass (Staffanstorp) (■) ; BASF (Ludwigshafen) (▲) and DESY (Hamburg) (●) ; open triangles are for evacuated aerogels; sintered aerogels (●) ; generally display the largest sound velocities for a given density.
These scaling laws can either be explained in terms of percolation theory, or as a result of the fractal network structure. The considerable deviations of the elastic properties for a given density are due to the degree of connectivity on the nanometer scale, resulting from different preparation conditions or sintering.

Additionally, the shear and rupture moduli display scaling with the density, whereas the Poisson ratio \( \mu \approx 0.22 \) is independent of density.

4. Applications

All aerogel applications make use of their high porosity and nanostructure, which are responsible for the small index of refraction, the small Young's modulus, the huge inner surface and the small thermal conductivity. In some applications, a high optical transparency is also required. For carbon aerogels, the pronounced electrical conductivity is of importance.

4.1 Monolithic Si\(_2\)O\(_2\)-Aerogels

Most of the monolithic aerogels produced to date have been used in Čerenkov detectors. For the detection of fast pions, kaons or photons, a medium with refractive index \( n \approx 1 \) is required. Aerogels can be made with \( n \approx 1.005 \) to \( n \approx 1.1 \), which corresponds to densities from about 20 to 500 kg/m\(^3\) and thus happen to fit into the range of \( n \)-values that cannot be covered by compressed gases or liquids.

Also, the use of highly transparent aerogel sheets in windows was once considered feasible. However, since the production of large flat crack-free and transparent aerogel sheets is extremely difficult and expensive, this application does not seem very realistic today.

4.2 Granular and Powdery Si\(_2\)O\(_2\)-Aerogels

4.2.1 Transparent Thermal Insulation

Studies have shown that the thermal resistance and solar transmittance of granular silica aerogel fills or hot-pressed aerogel plates are sufficiently high to allow their application in transparent insulations (Figure 9). Aerogels for mass applications have to be cheap and thus only waterglass as a precursor can be used. The aerogel is introduced between two glass panes, and the solar radiation which passes through the aerogel/glass layer is absorbed by a black surface. The efficient thermal insulation of the aerogel fill cuts heat losses, and most of the produced thermal energy is available for heating purposes. To prevent overheating, a shading device is necessary. Another problem, the settling of the granular fill under atmospheric pressure changes, can be overcome by a partial evacuation.

4.2.2 Opacified Si\(_2\)O\(_2\)-Aerogel as Thermal Insulating Materials

A very promising idea is the application of opacified granular or powdered aerogels as a substitute for glass fibres or foams in thermal insulations, e.g. for refrigerators or heat storage systems.

Recently, a thermal phase-change storage system, which uses aerogel as a superinsulating layer, was developed by BMW and Längerer & Reich in Germany. The heat (700 Wh) stored in the system can be used to heat the cold motor, to warm up the passenger cell or to defrost the windscreen (Figure
The evacuated aerogel insulation has a thickness of only 10 mm with an effective conductivity of 0.003 W/(m·K), which results in total heat losses of about 6 Wh/h. The phase-change medium is an eutectic salt mixture of 90 weight % magnesium nitrate-hexahydrate and 10 weight % lithium nitrate.

One considerable advantage of powdery aerogels compared with micron-sized fumed or precipitated silicas are the better free-flow properties of aerogel powders especially when handled in vacuum. In Figure 11, the free-flow properties of an aerogel powder are compared with the free-flow properties of two different precipitated silicas ($d_{50} \approx 50 \mu m$ and $d_{50} \approx 5 \mu m$) at approximately 1 mbar. The curves were obtained by measuring the mass flow through a hopper which was placed in a vacuum chamber. To ensure a mass flow even for powders with bad free-flow properties, the hopper is additionally equipped with a stirring device. As Figure 11 shows, the mass flow of the aerogel and the coarse precipitated silica are comparable, however, the wiggles in the precipitated silica data indicate less favorable free-flow properties compared with the aerogel. In addition, the thermal conductivity of the coarse precipitated silica is larger than that of aerogel. This is due to the higher density of the precipitated silica particles. The thermal conductivity of the fine precipitated silica is comparable to the aerogel powder, but it has less favorable free-flow properties.

### 4.2.3 Miscellaneous

There are many other interesting applications of aerogels which have not been discussed so far, some of which are listed below:

1. Due to their nanostructure and large internal surface, they can be used as gas filters or as substrates for catalytic materials.
2. Small, high-velocity particles in space can be “softly” captured by low density aerogels.
3. Due to their thermal stability, silica aerogels are used as transparent moulds for melt casting.
4. Aerogels can be used for acoustic impedance matching layers in ultrasonic transducers.
5. Last but not least, carbon aerogels are promising as electrodes in electrical supercapacitors (Figure 12), which have especially large power densities.

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**Fig. 10** Aerogel-superinsulated phase change heat storage tank developed by Längerer & Reich/Germany.

**Fig. 11** Mass free flow of aerogel powder and two different precipitated silicas ($d_{50} \approx 50 \mu m$ and $d_{50} \approx 5 \mu m$).
Fig. 12 Mass specific power versus mass specific energy for different energy storage and conversion systems.

5. Nomenclature

| Symbol   | Definition                                      |
|----------|------------------------------------------------|
| a        | mass flow (kg/s)                                |
| D        | mass fractal dimension                          |
| Ds       | surface fractal dimension                       |
| d_90     | median particle diameter                        |
| E        | specific extinction at 630 nm (m²/kg)           |
| E_68     | specific extinction coefficient in the IR-region |
| k        | heat transfer coefficient (W/(m²K))             |
| l_68     | photon mean free path (m)                       |
| n        | refractive index (1/m)                          |
| q        | scattering index (1/m)                          |
| R        | cluster size (m)                                |
| r        | particle size (m)                               |
| T        | temperature (K)                                 |
| v_0      | sound velocity (m/s)                            |
| Y        | Young's modulus (N/m²)                          |
| a, b, γ  | scaling constants ( - )                         |
| φ_g      | grain/void size (m)                             |
| λ        | wavelength (m)                                  |
| λ_e      | gaseous thermal conductivity (W/(mK))           |
| λ_r      | radiative conductivity (W/(mK))                |
| λ_s      | solid thermal conductivity (W/(mK))             |
| μ        | Poisson ratio ( - )                             |
| θ        | scattering angle (°)                            |
| ρ        | density (kg/m³)                                 |
| σ        | Stefan Boltzmann constant (W/(m²K))            |
| da/dΩ    | mass specific cross section (m²/(kg srad))      |

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