Solar Active Plaster for the Renovation of Existing Buildings

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Introduction

Using the solar energy as an energy source within building walls is the main goal of this study. In conventional building construction, the energy balance of walls is improved by increasing the thickness of the insulation layers. In the case of existing buildings, characteristic façade details will often be destroyed due to insulation layers with considerable thickness. Bringing solar energy more effectively into the wall, the thickness of the insulation layer can be decreased. The activation of thermal masses, often present in existing buildings, then is possible to improve the energy balance. In addition, smaller thicknesses help at the conservation of characteristic façade details. For this proposal, the development of a semitransparent insulation layer will be studied. The basic idea is that the insulating character of the material will be generated by the use of hollow glass spheres with a vacuum/air filling. The glass spheres show a good insulation effect. The medium in which the glass spheres will be placed (filler material) is a semitransparent medium. The transmittance of light should result in a temperature increase at the point of absorption (between the insulation layer and the brick wall) and thus energy could be stored. The heat flux through the wall will be reduced by the smaller temperature gradient concurrent in the brick wall.

This work discusses material parameters that will influence the transmittance of light through the semitransparent medium. The discussion relates to the wall thickness of the spheres, the radius of the spheres, the degree of filling, the extinction coefficient of the matrix and the angle of incidence of the rays.

The results can be used as a basic guideline for the development of a semitransparent plaster. In addition, the feasibility can be derived from the findings.

Similar studies of the idea of adding particles to improve the light transmittance have been made by [1]. The study showed that for highly porous aerogel particles (non-hollow) the transmittance is depending on the size of the added particles. By doubling the particle size, the transmission within the observed thickness was tripled. A related study was made by [2] with glass particles within an epoxy matrix. The measured findings resulted in similar effects by consideration of the particle size. Increased diameters resulted in increased light transmittance. The thermal conductivity of silica hollow spheres based on their density has been studied in other works, e.g. [3], and is not part of this work. The modification of hollow spheres by metal coatings to influence the transmittance of light by means of wavelength [4,5] will be studied subsequent reports.

The examination for the use of hollow spheres in plaster type materials with thicknesses over 2 [cm] has not been examined yet and thus this work will focus on the needs of such materials.

Theory

The path of light through the surface of objects and them itself can for many cases be reduced to the basic effects of refraction and reflection. Reflection and refraction at material discontinuities are covered by the Fresnel equations and the Snell´s law. The reflection (transmission) can be calculated for s- and p-polarized light by equation (1) and (2).

$$r_s = \frac{n_1 \cos(\theta_i) - n_2 \cos(\theta_t)}{n_1 \cos(\theta_i) + n_2 \cos(\theta_t)} \qquad (1)$$

$$r_p = \frac{n_2 \cos(\theta_i) - n_1 \cos(\theta_t)}{n_2 \cos(\theta_i) + n_1 \cos(\theta_t)} \qquad (2)$$

with

r_s Reflectance of s-polarized light
r_p Reflectance of p-polarized light
n_1 Refractive index before the material discontinuity
n_2 Refractive index after the material discontinuity
$\cos(\theta_i)$ Angle between the incident ray and the normal to the material discontinuity
$\cos(\theta_t)$ Angle between the transmitted ray and the normal to the material discontinuity

Thus the intensity for the transmitted and reflected parts through surfaces can be calculated by the equations (3) and (4):

$$I_t = \frac{n_2 \cos(\Theta_t)}{n_1 \cos(\Theta_i)} I_i \left|t_{p/s}\right|^2 \quad (3)$$

$$I_r = I_i \left|r_{p/s}\right|^2 \quad (4)$$

with

t_s Transmittance of s-polarized light
t_p Transmittance of p-polarized light
I_t Intensity of the transmitted ray
I_r Intensity of the reflected ray

These equations are used in the Ray Optics Module™ but neglect the occurrence of diffraction (which is not needed for the solving). Since the observation treats a semitransparent medium, the attenuation within domains becomes relevant for consideration. The attenuation can be described by the equations (5) and (6):

$$|E| = |E_0| e^{\left(-\frac{2k_0 KL}{N}\cos\propto\right)} \quad (5)$$

$$I = I_0 e^{\left(-\frac{2k_0 KL}{N}\cos\propto\right)} \quad (6)$$

with

$|E|, |E_0|$ Eletric Field
L optical path length between E and E_0.
k_0 wave vector in free space

Since the matrix is weakly absorbing, the parameters N, K and $\propto$ become:

$$N = n \quad (7)$$

$$K = k \quad (8)$$

$$\propto = 0 \quad (9)$$

with

n real part of the complex refractive index
k complex part of the complex refractive index
$\propto$ angle between the surfaces of constant amplitude and surfaces of constant phase

The applicability of the raytracing-algorithm for this study is based on the following rules gathered by [6]:

- The particle size must be much greater than the radiation wavelength
- The roughness of the surfaces is considerably smaller than the wavelength of the radiation
- The distance between single particles has to be much greater than the particle size
- Effect of diffraction doesn´t have to be considered for the solution of the problem
- Physical effects occurring can be reduced on the effects of absorption, emission and scattering.

Simulation Model

Within the Application Builder Tool™ the creation of the simulated matrix and the filler material can be coded and executed. The simulation model can be seen in Figure 1.

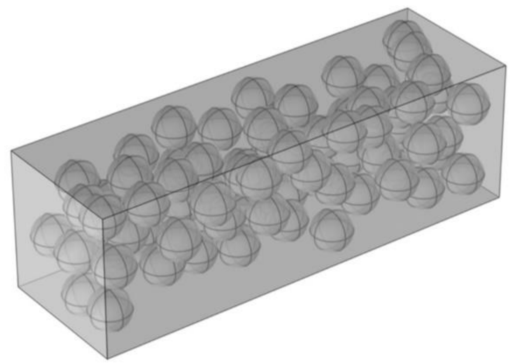

Figure 1. Simulation model

The hollow spheres are created by a model method and the code is a modification and extension of the code presented in [7]. The modified code is able to create hollow spheres with a random distribution within a plaster block. The hollow glass spheres are checked for collision with each other. The spheres are nevertheless allowed to touch each other. A loop counts the tries to create the spheres and stops after a critical amount is exceeded. The stop condition is needed for a high degree of fillings because under non-optimized conditions the hollow spheres can block free space as well as a maximum degree of filling can be transcended. All spheres are placed within a limited box, the plaster. The code directly assigns materials from the material database to the created objects. In addition, a Gaussian function for the distribution of the particle size and wall thickness can be easily applied if needed.

The materials within the hollow spheres are vacuum/air and the glass type of the spheres' walls is made of borosilicate glass. The matrix is based on a

non-real binder material, which gets set values. For the simulation, it is important to determine the amount of light that enters the simulation-box on the entry boundary layer and how much power/intensity is transmitted through the semitransparent material towards the opposite side. The remaining sites of the box are treated as surfaces with specular reflection to keep the energy balance in check (light will be lost and gained through neighbouring plaster areas).
Since the application of the solar plaster aims for a thickness as small as possible, the chosen depth of the plaster is 4 [cm].

Simulation Results

The observed parameters have been listed in the introduction section. Figures 2 – 6 illustrate the transmitted intensity as a function of the respective parameters. The light transmission is studied for a wavelength of 660 [nm]. The default conditions for the discussion are:

- radius of the spheres is set to 2 [mm]
- wall thickness equals 0.1 [mm]
- extinction coefficient of the host medium is set to 1.4758E-5 [-]
- angle of incident radiation is 0 [°]
- degree of filling is equal to 20.5 [%]

During the observations, only one of the parameters is changed at a time and is reset to default after the examination is finished.
Firstly, the effectivity of the solar active plaster is studied dependent on the degree of filling. A high degree of filling results in a high amount of boundary layers as well as the distance within the domain that the ray strides, is risen. Hence, the transmitted power decreases with an increasing number of hollow spheres (see Figure 2).

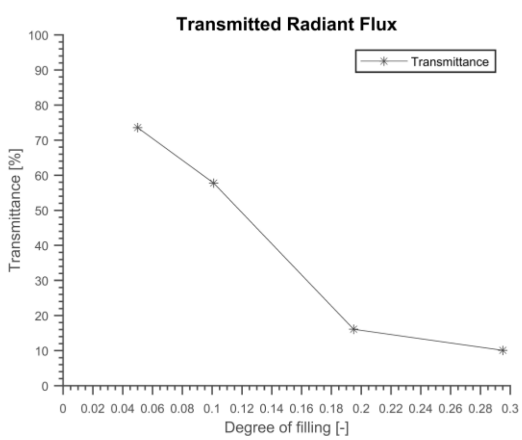

Figure 2. Transmitted power dependent on the degree of filling.

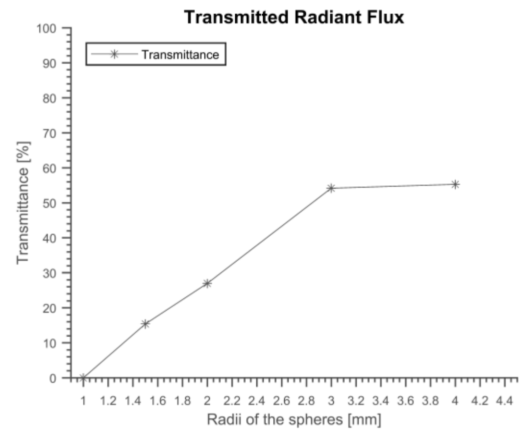

Figure 3. Transmitted power dependent on the sphere radius.

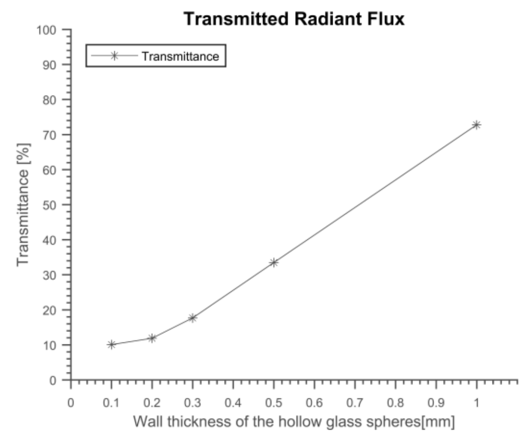

Figure 4. Transmitted power dependent of the sphere´s wall thickness.

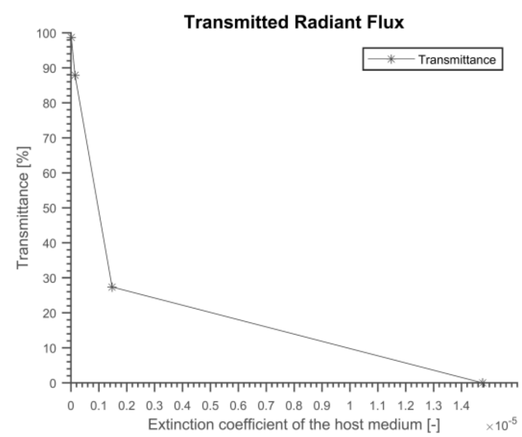

Figure 5. Transmitted power dependent on the mediums extinction coefficient

By increasing the degree of filling from 10 [%] to 30 [%] the transmittance is reduced by nearly 60 [%]. The second parameter to be examined is the transmitted power over the radius of the outer sphere.

Increasing the radius of the spheres, by the same degree of filling, the number of spheres is reduced and thus the material discontinuities (reflection and refraction) that are encountered is drastically decreased. The overall transmitted light therefore is positively influenced. After reaching the radius of 3 [mm] in this special case of having a block with the size of 10 x 10 x 40 [mm] the number of the boundary layers doesn´t change that much with increasing sphere sizes (see Figure 3) and the achievable improvements are limited.
The same effect can be seen in the observation of the spheres' wall thickness. If the wall thickness is increased, the rays are less likely to face as many material discontinuities as with smaller wall thicknesses. This can be explained due to the fact that rays are not moving into the hollow part of the sphere. They remain in the glass part and the object is treated as a full-glass sphere. The transmittance is linearly rising between the wall thickness of 0.3 [mm] up to 1 [mm].
In contrast, for hollow glass spheres filled with air the absorption of the objects as a whole is very small. For the transmission, the extinction coefficient of the host material is defining for the efficiency of the light transmission. By decreasing the extinction coefficient by the power of -1 the transmitted power drastically increases, as illustrated in Figure 5. The graph mirrors the large exponential decline that follows expected behaviour.
Another point to consider for solar active plaster is that the angle of incidence of solar radiation will shift between a solar angle of 0 [°] up to a height at maximal 30 [°] in winter months and up to 63 [°] in the summer months. Where in the summer a high transmittance shows negative effects, in winter this is highly advantageous. The transmittance should show lower factors for high incident angles. Figure 6 confirms, that between angles of 12,5 [°] and 63 [°] the transmittance is reduced by more than 10 %.

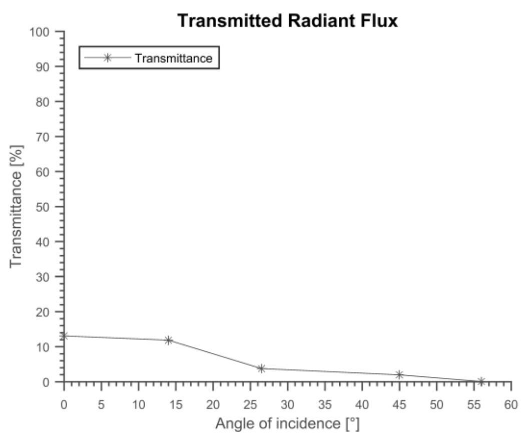

Figure 6. Transmitted power dependent on the rays incident angle.

Conclusion

The study clearly shows that a solar plaster, in theory, can transmit pertinent amounts of solar radiation under the given restrictions. By setting the efficiency of solar active plaster to a light transmittance of 20 – 30 % it is shown, that a solar active plaster with a thickness of 4 [cm] is makeable. Otherwise, by now, the two most restricting factors are the requirement of the low extinction coefficients for the host medium (binder material) and the size of the hollow glass spheres.
Thus, for future study steps, the effects of using full-glass spheres in contrast to hollow spheres have to be examined. Using full spheres will lead to massively increased thermal conductance and therefore provide further problems that need to be solved. The need for an optical acceptance by the users of the existing buildings is another point that must be discussed in further works.
A solar active plaster that can transmit enough solar radiation to be efficient should follow the determined rules:

- The extinction coefficient of the host medium should/must be as low as possible
- The wall thickness of the spheres should be high

The number of boundary layers within the plaster should be as low as possible and therefore the following points can be concluded:

- The radius of the spheres should be as large as possible
- The degree of filling should be as low as possible (without losing the effect of the angular transmission; that needs to be examined in another study)

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