THE INVESTIGATION OF USING PHASE CHANGE MATERIAL FOR SOLAR POND INSULATION

by

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Solar ponds are systems that store solar energy in salt water as heat energy. In order to store heat energy for a long time in solar pond, the heat insulation should be done well. In this study, the effect of phase change materials was investigated to improve the insulation of the pond and to store the heat energy for a longer time. The melting temperature is a key parameter in the selection of phase change materials. The temperature distribution of the solar pond was examined and phase change materials with melting temperatures in the range of the pond average temperature ±10 °C were selected. Three different phase change materials were used in the walls of the solar pond for insulation. The temperature and enthalpy changes of the system were calculated numerically for a year. The heat storage ratio of the solar pond was determined by using the obtained enthalpy and solar radiation data. Consequently, the heat storage ratio of the pond with glass-wool is maximum 20.95% in July and minimum 7.92% in January. The heat storage ratio of the solar pond which paraffin C18, capric acid and paraffin 44 are used as phase change materials is maximum 32.22%, 34.85%, and 47.81% in December, respectively. It is observed that the appropriate selection of phase change materials is provided a longer storage time for solar ponds.

Key words: *solar energy, solar pond, thermal energy, heat transfer, heat exchanger*

Introduction

The energy consumption of people is increasing rapidly with the increasing population and technological developments. However, the decrease in conventional energy sources increases people's interest in RES. Solar energy, the origin of other energy sources, comes to the fore in this regard. Obtaining thermal energy from solar energy is one of the practices that existed for a long time. Solar ponds are one of the solar energy applications which heat is stored in salty water. Research is ongoing to improve the efficiency of solar ponds and to store heat longer. Wang *et al.* [1] investigated the effect of porous media on the efficiency of the solar pond. The porous media was added in the heat storage zone and 1-D transient temperature, energy and exergy models were developed. It is indicated that adding porous media with low volume heat capacity and low heat diffusivity to the heat storage zone is beneficial for higher temperature. Silva *et al.* [2] suggested using transparent partial covers to decrease evaporation for solar ponds. The effects of evaporation on the water and energy balance were

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investigated. The heat storage capacity of the system was improved by using transparent partial covers. Sayer *et al.* [3] investigated the effect of evaporation on heat loss from the surface of a solar pond. Evaporation increases the cost of the system as well as decreasing its performance. To eliminate evaporation, a solar pond with a thin layer of paraffin on the surface of the system was constructed. It was demonstrated that the air temperature, solar radiation and humidity have a significant effect on evaporation. Berkani *et al.* [4] studied three experimental solar ponds with different salts. The thermal performance of the three solar ponds was studied numerically and experimentally during a month. It was demonstrated that the solar pond with $CaCl_2$ responds thermally more quickly than the others. Bozkurt *et al.* [5] studied a solar pond saturated with magnesium chloride experimentally. The energy and exergy content distributions were calculated for the lower convective zone and the non-convective zone and the energy and exergy performance were determined. Assari *et al.* [6] examined the shadow effect for solar ponds with different shapes. The solar ponds with the same surface area and volumes were constructed experimentally. It was indicated that the shadow is smaller in the rectangular type solar pond. Verma *et al.* [7] studied the effect of the wall profile on the efficiency of the solar pond. The linear, concave parabolic and convex parabolic walls with circular and square cross-sections were analyzed for specific area and volume. It was determined that the vertical wall offers more efficiency than the other geometry. Alcaraz *et al.* [8] evaluated heat supply from solar thermal collectors to solar pond under different conditions. It was determined that the use of solar collectors as a heat supply source led to increase the heat storage capacity and its overall performance efficiency. Sogukpinar [9] determined the solar pond's power potentials for different areas in Turkey. The temperature distribution was calculated by using finite element method. Sogukpinar [10] developed solar pond models to investigate the efficiency of the pond for different cases. The zones were composed of the freshwater to make it useful with preserving performance.

Studies are ongoing to use phase change materials (PCM) in order to store heat in the pond for a longer time. Assari *et al.* [11] suggested adding PCM to lower convective zone of the solar pond. The solar ponds with the same area and depth were constructed. The capsules containing paraffin wax were placed in the lower convective zone of the system. It was shown the pond with paraffin wax decreases the temperature difference between night and day. The solar pond has more thermal and salinity stability, when the PCM were used. Alcaraz *et al.* [12] evaluated heat extraction from the zones of a solar pond to enhance the performance under different conditions. The lateral wall was used as a heat exchanger and its efficiency was compared with conventional heat exchanger situated in the lower convective zone of the solar pond. It was indicated that the performance of the solar pond increases when the lateral heat exchanger was used or using both heat exchangers simultaneously. Sarathkumar *et al.* [13] investigated the effect of PCM with Al_2O_3 nanoparticles on the performance of a solar pond. The PCM and Al_2O_3 were encapsulated into the Cu tube and they were placed in the lower convective zone. Ines *et al.* [14] investigated the thermal behavior of a solar pond exposed to a solar simulator in environmental chamber. The efficiency of the pond was calculated taking into account the influence of simulator spectrum. It was indicated that the solar pond with salt hydrates could use as a hot water source for domestic applications. Amirifard *et al.* [15] studied a solar pond integrated with latent heat storage to increase the performance of the solar pond. The energy balance equation of the system was written and solved by using the finite difference method. The parallel and a series layout were studied and validated the results with the experiment for the accuracy of the analysis. Beik *et al.* [16] suggested using PCM in lower convective zone of the pond to seek its effect. The capsules with paraffin wax were placed in lower convective zone of the solar pond. It was indicated that using PCM in the solar pond causes more stable temperature.

Many studies have been performed to increase the performance of the solar pond with different sizes and features. However, PCM have been used only in a few studies of the solar ponds. In the literature, the PCM were added to the lower convective zone of the pond and used as a lateral heat exchanger to provide the thermal stability. In this study, the use of PCM was investigated to improve the heat storage period of the solar pond. For this purpose, PCM were placed in the wall of the solar pond to provide a longer storage time. The effect of PCM with different properties on improving the heat storage ratio of the solar pond was determined numerically and compared with the solar pond without PCM.

Solar ponds

Solar ponds are systems that store solar energy in salty water as heat energy. Solar ponds generally consist of three regions, namely heat storage zone (HSZ), non-convective zone (NCZ), and upper convective zone (UCZ). The HSZ is the region where the heat energy is stored and consists of saturated salty water. The NCZ starts from where HSZ ends. The NCZ consists of layers decreasing density towards the surface. These layers prevent heat transfer by convection. The UCZ is the surface zone of the pond and consists of fresh water.

The numerical simulation was performed for a solar pond and compared with the experiment data for the same dimensions and location. The experiment was conducted [17] in Adana with dimensions of 2 m × 2 m × 1.5 m. The experimental system was constructed with a surface area of 4 m^2 and insulated by 0.05 m glass-wool. Brine density varies from 1045-1170 kg/m^3 and it varies from 1170-1200 kg/m^3 in NCZ. As seen in fig. 1, the height of UCZ, NCZ, and HSZ are 0.10 m, 0.50 m, and 1 m, respectively. The UCZ was composed of freshwater. The NCZ consists of five different brine layers with a depth of 0.10 m and density of brine varies between 1030 kg/m^3 and 1150 kg/m^3, it was defined as 1180 kg/m^3 in HSZ. The 0.10 m concrete was defined for the wall of the pond and the wall surface was covered externally with 0.10 m insulation material. In the current study, since the contribution of the different types of insulation materials was investigated on the heat storage capacity of solar pond therefore foam or phase changing material were defined for the insulation. These materials are surrounded by 0.001 m wall thickness plastic cover to prevent their contact with water. Capric acid, paraffin C18 and paraffin wax are chosen as PCM materials and their thermophysical properties are given in tab. 1 [18, 19].

Table 1. Thermophysical properties of PCM

Materials	Melting temperature [°C]	Latent heat of fusion [kJkg^{-1}]	Solid density [kgm^{-3}]	Liquid density [kgm^{-3}]	Thermal conductivity [Wm^{-1}K^{-1}]
Capric acid	32	152.7	1004	878	0.153
Paraffin C18	28	244	814	774	0.148
Paraffin wax	44	190	930	830	0.1

For the ambient data, meteorological data ASHRAE 2013 was used. The surface to surface radiation method was set to hemicube, and radiation resolution was set to 256, initial values was taken as 1000 W/m^2. For the participation media, the radiation discretization was set to the discrete ordinate method (DOM). The refractive index was taken as 1, and the performance index was taken to 0.40. The PCM, solar pond wall surface were defined as opaque surface and wall type was set to gray wall with a surface emissivity of 0.01. For the radiation in participating media setting, absorption and scattering coefficients were taken from COMSOL material library. For the external radiation source, the solar position was determined. For the environmental data, temperature, wind speed, and the pressure were taken. On the solar pond surface, natural external convection was defined. For this, external temperature and the pressure were defined from the meteorological data of Adana from ASHRAE 2013. For the PCM settings, phase change temperature, latent heat of fusion, thermal conductivity were defined for both state and data were taken from literature. A thin layer was defined over the PCM and the insulator materials by a thickness of 1 mm. In this study, direct solver PARDISO (a commercial version built-in COMSOL) with nested dissection multithreaded preordering algorithm was used due to its performance, robust, memory efficient and easy to use software for solving large sparse symmetric and unsymmetrical linear systems of equations on shared-memory and distributed-memory multiprocessors [10]. The method uses a large amount of RAM and processor as it makes a separate solution for each mesh point. Other methods, such as RANS, analyze for the mean values of the variables, and the effect of all scales of instantaneous thermal motion is modeled with an approximate model of the mean. Since it uses the average approach, it uses less RAM and processor, and the mesh count of such models is kept quite high. On the other hand, when the mesh number increases a little more in direct analysis models, it becomes impossible for normal computers to solve. The mesh number was determined by taking into account other scientific studies using the same model [9, 20-22]. The COMSOL mesh module was used for grid generation. Tetrahedral mesh type was chosen and the element size was set to coarse. Quality of mesh was tested in terms of skewness and the average element quality was determined as 0.49 [23]. The final mesh distribution is presented in fig. 1. Direct solver PARDISO was chosen because of its high performance [24]. For the preordering algorithm, nested dissection multithread was set and for the termination technique, tolerance was set and the maximum iteration was chosen as 10. The time unit of study setting was chosen as day and the time range was arranged as 30 days.

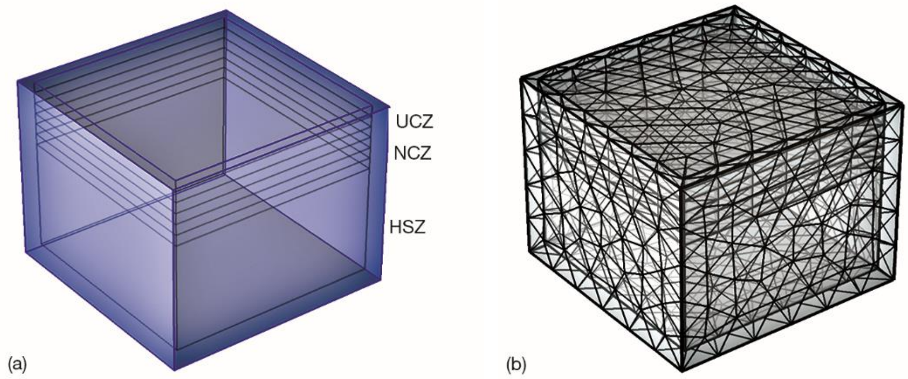

Figure 1. The zones of the pond (a) and mesh distribution (b)

The performance of the solar pond depends on factors such as its insulation, design of the zones, incoming solar energy and environmental temperature. Solar energy is collected and stored in HSZ as heat energy. Total energy stored in HSZ was determined by using enthalpy values. Heat storage ratio (HSR) of the solar pond was calculated:

$$HSR = \frac{\sum Q_{\text{stored}}}{\sum E_{\text{solar}}} = \frac{\sum m_{\text{HSZ}} h}{\sum E_{\text{solar}}} \quad (1)$$

where E_{solar} is the solar radiaton reaching the pond surface, m_{HSZ} – the mass of HSZ, and h [kJkg^{-1}] – the enthalpy.

Phase change materials

The PCM are matter that absorb or release a large amount of latent heat when they undergo a change in their physical state from solid to liquid or vice versa and they release or absorb sufficient energy at phase alteration to supply useful heat or cooling. When the PCM reach their phase change temperature, T_{pc}, transformation starts in temperature interval from $T_{\text{pc}} - \Delta T/2$ to $T_{\text{pc}} + \Delta T/2$. Given the phase change in solid, the density is determined within framework of the material and a smoothed function, θ, is used for model, showing the partition of phase change before alteration. The density of the different phases are defined as ρ_{ph1} and ρ_{ph2}, respectively. The expression of the density of material simplifies to:

$$\rho = \theta \rho_{\text{ph1}} + (1-\theta)\rho_{\text{ph2}} \quad (2)$$

Specific enthalpy, h, of a PCM express by:

$$h = \frac{1}{\rho}[\theta \rho_{\text{ph1}} h_{\text{ph1}} + (1-\theta)\rho_{\text{ph2}} h_{\text{ph2}}] \quad (3)$$

where h_{ph1} and h_{ph2} are specific enthalpy of each phase. Specific heat capacity is calculated by differentiation enthalpy by temperature and is expressed by eq. (4) after differentiation and some formal transformations [25]:

$$C_p = \frac{1}{\rho}(\theta_1 \rho_{\text{ph1}} C_{p,\text{ph1}} + \theta_2 \rho_{\text{ph2}} C_{p,\text{ph2}}) + (h_{\text{ph2}} - h_{\text{ph1}})\frac{\mathrm{d}\alpha_{\text{m}}}{\mathrm{d}T} \quad (4)$$

where α_{m} is a mass function, defined from smoothed function θ, ph1, and ph2.

Theory of radiation into solar pond

In most implementation, the radiation beams interact with environment because it is not transparent completely. Let's $I(\Omega)$ state the intensity of the radiation moving in a certain direction Ω and different interactions with the medium is observed. They are absorption, emission and also scattering. The medium absorbs some of the incoming solar energy. The quantity of radiation absorbed is $\kappa I(\Omega)$, where κ is the absorption coefficient. The emitted amount of radiation is equal to κI_{b}, where I_{b} is the blackbody radiation intensity. The scattering phase function $\varphi(\Omega, \Omega')$ gives the possibility of the beam coming from Ω' and scattered into Ω direction. The balance of the energy intensity, which includes all additives (diffusion, emission, absorption, and scattering), and can now be expressed as:

$$\Omega \nabla I(\Omega) = \kappa I_{\text{b}}(T) - \beta I(\Omega) + \frac{\sigma_s}{4\pi}\int_{4\pi} I(\Omega')\varphi(\Omega', \Omega)\mathrm{d}\Omega' \quad (5)$$

where β is extinction coefficients and σ_s – the scattering coefficient. The intensity of radiation is described for any direction Ω. Due to the angular space discretization, the integrals on the directions are replaced by the numerical quadrature of the discrete directions. The DOM uses the following eq. (6) for the discretization of angular space in 3-D [26, 27]:

$$S_{i^+}\nabla I_{i^+} = \kappa I_b(T) - \beta I_{i^+} + \frac{\sigma_s}{4\pi}\sum_{j=1}\omega_j I_j \varnothing(S_j, S_{i^+}) \tag{6}$$

where S_i is the i^{th} discrete direction (Si^+, and Si^- shows opposite directions), ω_j – the i^{th} quadrature weight, and I_j – the i^{th} component of the radiative intensity. For a given index i, defines two indices, i^+ and i^-, so that Ω, Si^+, and Si^- have the same components in the x-y plane and have opposite components. The heat transfer in solids and liquid was calculated by:

$$\rho C_P\left(\frac{\partial T}{\partial t} + \mathbf{u}\nabla T\right) + \nabla(\mathbf{q} + q_r) = \alpha_p T\left(\frac{\partial p}{\partial t} + \mathbf{u}\nabla p\right) + \tau : \nabla\mathbf{u} + Q \tag{7}$$

where ρ is the density, C_P – the specific heat capacity, T – the temperature, $\mathbf{u}$ – the velocity vector, $\mathbf{q}$ – the heat flux by conduction, q_r – the heat flux, and α_p – the coefficient of thermal expansion.

Results and discussion

The use of PCM is very important for long-term storage of thermal energy in solar ponds. The PCM can store heat energy as latent heat at desired temperature for a long time. Thus, it is possible to store the solar radiation stored in the summer for a longer time. In this study, the use of different PCM as thermal insulation material was investigated and compared with the traditional thermal insulation method. Solar energy and temperature data of Adana, which is rich in solar energy and has mild weather conditions, were used. Figure 2 shows solar energy and environmental temperature in Adana, Turkey. The maximum and minimum solar energy is 713.91 MJ/m^2 in June and 218.48 MJ/m^2 in January, respectively. The maximum and minimum average environmental temperatures are 30.79 °C in August and 11.29 °C in January, respectively.

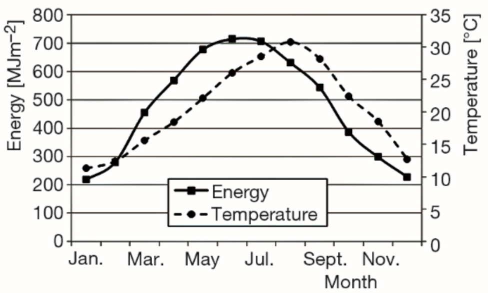

Figure 2. Solar radiation and environmental temperature distribution in Adana, Turkey

The numerical simulation was performed for a solar pond and compared with an available experiment as shown in fig. 3. The experiment was conducted in 2004 [17] in Adana with dimensions of 2 m × 2 m × 1.5 m. The experimental system was constructed with a surface area of 4 m^2 and insulated by 0.05 m glass-wool. Brine density varies from 1045-1170 kg/m^3 and it varies from 1170-1200 kg/m^3 in NCZ. Temperature variation was measured in several parts and the average was reported. A similar configuration with the experiment was defined to the numerical model and average temperature was calculated in HSZ and reported. Generally, there is a good agreement between numerical results however, there are deviations in some time periods as shown in fig. 3. The first 30 days in the chart represent March. Especially in winter, heavy rainfall negatively affects the performance of the solar pond. The difference between experimental and theoretical calculations is due to these weather phenomena. The last two points are indicative of the month of January and February, which are different from the theoretical value, but generally there is a good agreement between experiment and theory.

The effect of three different PCM on the thermal efficiency of the solar pond was investigated numerically and the results are given in fig. 4 in comparison with the glass-wool. Figure 4 shows the average temperature of HSZ of the pond and fig. 5 shows the mean enthalpy of the HSZ. The performance of the solar pond material is significantly reduced in winter covered with conventional insulation however performance increases considerably with PCM. Paraffin wax shows the best performance while paraffin C18 shows the worst. In a preliminary analysis, the wall surface temperature without PCM ranged from 25 °C to 35 °C. Hence the materials were selected according to this temperature range. The effect of the melting temperature of PCM on performance is clearly seen in fig. 3. The melting temperature of paraffin wax is 44 °C, it stored heat at high temperature on the wall surface and kept the pond temperature high during the winter months.

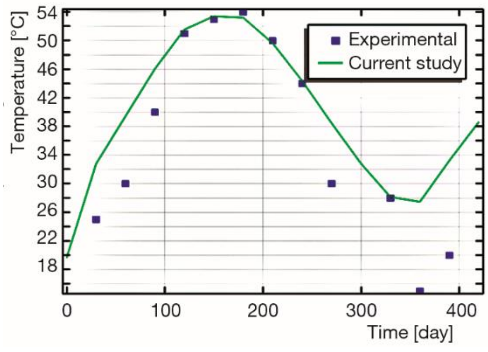

Figure 3. Average temperature distribution in the solar pond; first 30 days is March

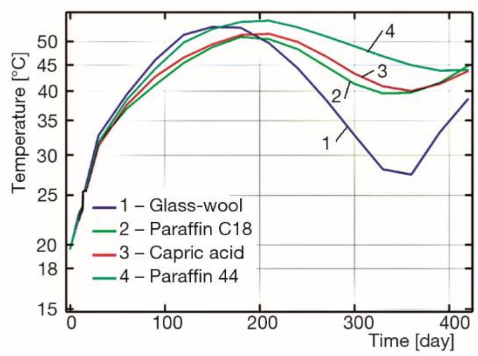

Figure 4. Average temperature distribution in the solar pond

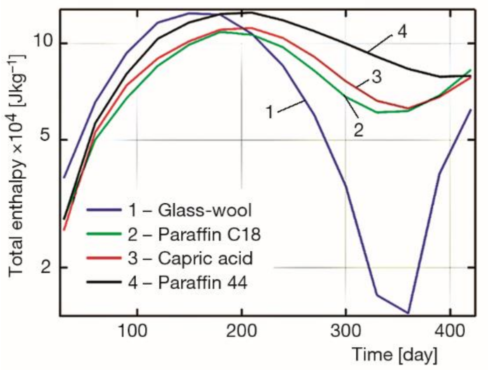

Figure 5. Average enthalpy distribution in the solar pond

Figure 6 shows the total energy distribution stored in the storage zone of the solar pond. As seen in fig. 6, the energy stored in the storage zone of the solar pond is increasing rapidly, with the increase in incoming solar energy until June. It is seen that the energy stored in the solar pond using glass-wool has started to decrease as of July. In addition, the increase in heat stored in the solar pond using PCM is continued until August. It is seen that the energy stored in the solar pond using glass-wool has entered a rapid decline trend after September. However, the decrease in energy stored in the pond where PCM is used as insulation material is slower.

Figure 7 shows HSR of the solar pond. As seen in fig. 7 the HSR of the solar pond with PCM is lower than the solar pond with glass-wool until August. The fact that the system has just started to store heat and PCM have not yet begun to change the phase has been effective in this. Although the HSR of the solar pond with glass-wool started to decrease rapidly with the cooling of the weather since October, it is seen that the HSR of the solar pond with PCM continued to increase until December. It is understood that in months when solar energy is high, the stored heat can be retained for a long time by using PCM. It is seen that the HSR of the solar pond with glass-wool is maximum 20.95% in July and minimum 7.92% in January. The HSR of the solar pond which Paraffin C18, Capric acid, and Paraffin 44 are used as PCM is maximum 32.22%, 34.85%, and 47.81% in December, respectively. It is seen that with the use of PCM, heat is stored in the solar pond for a longer time, at the same time the rapid decline in solar energy ensures that the HSR remains high for a longer time.

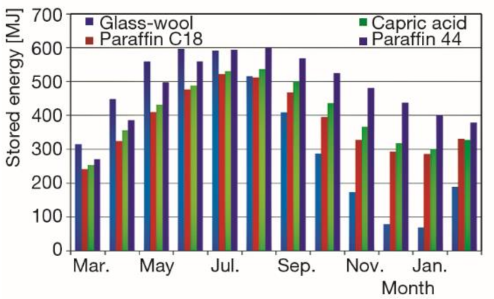

Figure 6. Total stored energy in HSZ

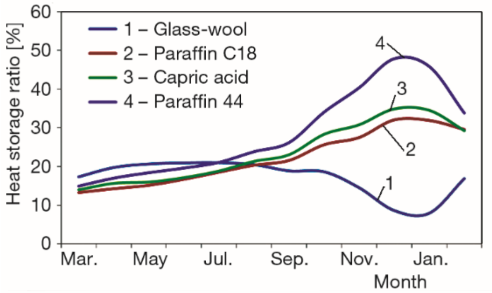

Figure 7. The HSR of the solar pond

Conclusion

Solar energy can be stored as thermal energy in solar ponds. However, the system needs to be improved for long-term storage. In this study, the use of PCM was investigated in order to keep the heat stored in the solar pond in the summer at the desired temperature level for a longer time. For this purpose, three different PCM with different phase change temperatures and thermophysical properties were used in the solar pond for insulation purposes. The temperature and enthalpy values obtained are given comparatively. The heat storage ratio was calculated by using the total enthalpy of the storage zone and the incoming solar energy. It is seen that the HSR of the solar pond with glass-wool is maximum 20.95% in July and minimum 7.92% in January. The HSR of the solar pond which paraffin C18, capric acid, and paraffin 44 are used as PCM is maximum 32.22%, 34.85%, and 47.81%, respectively in December. As a result, it has been determined that the use of PCM will allow the storage of heat energy stored in solar pond for a longer time.

Nomenclature

C_p – specific heat capacity at constant pressure, [$\mathrm{Jkg^{-1}K^{-1}}$]
E_Ω – internal energy, [J]
h – enthalpy, [$\mathrm{kJkg^{-1}}$]
$I(\Omega)$ – radiative intensity at a given position following the Ω direction, [$\mathrm{Wm^{-2}sr^{-1}}$]
$I_b(T)$ – blackbody radiative intensity, [$\mathrm{Wm^{-2}sr^{-1}}$]
p – pressure, [Pa]
$\mathbf{q}$ – heat flux by conduction, [$\mathrm{Wm^{-2}}$]
Q – heat sources other than viscous heating, [$\mathrm{Wm^{-3}}$]
q_r – heat flux striking the wall, [$\mathrm{Wm^{-3}}$]
S – strain-rate tensor, [$\mathrm{s^{-1}}$]
T – absolute temperature, [K]
$\mathbf{u}$ – velocity vector, [$\mathrm{ms^{-1}}$]

Greek symbols

β – extinction coefficients, [$\mathrm{m^{-1}}$]
κ – absorption coefficients, [$\mathrm{m^{-1}}$]
σ_s – scattering coefficients, [$\mathrm{m^{-1}}$]
τ – cauchy stress tensor deviatoric, [Pa]
$\varphi(\Omega', \Omega)$ – scattering phase function, [–]
ρ – density, [$\mathrm{kgm^{-3}}$]

Abbreviations

DOM – discrete ordinate method
HSR – heat storage ratio
HSZ – heat storage zone
NCZ – non-convective zone
UCZ – upper convective zone
PCM – phase change materials

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