Modulation of interfacial thermal transport between fumed silica nanoparticles by surface chemical functionalization for advanced thermal insulation

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ABSTRACT

Since solid-state heat transport in a highly porous nanocomposite strongly depends on the thermal boundary conductance (TBC) between constituent nanomaterials, further suppression of the TBC is important for improving performance of thermal insulators. Here, targeting a nanocomposite fabricated by stamping fumed silica nanoparticles, we perform a wide variety of surface functionalization on fumed silica nanoparticles by silane coupling method and investigate the impact on the thermal conductivity ($K_m$). The $K_m$ of the silica nanocomposite is about 20 and 9 mW/m/K under atmospheric and vacuum condition at the material density of 0.2 g/cm$^3$ without surface functionalization, respectively, and the experimental results indicate that the $K_m$ can be modulated depending on the chemical structure of molecules. The surface modification with a linear alkyl chain of optimal length significantly suppresses $K_m$ by about 30%, and the suppression can be further enhanced to about 50% with the infrared opacifier. The magnitude of suppression was found to sensitively depend on the length of terminal chain. The magnitude is also related to the number of reactive silanol groups in the chemical structure, where the surface modification with fluorocarbon gives the largest suppression. The surface hydrophobization merits thermal insulation through significant suppression of the TBC, presumably by reducing the water molecules that otherwise would serve as heat conduction channels at the interface. On the other hand, when the chain length is long, the suppression is counteracted by the enhanced phonon transmission through the silane coupling molecules that grows with the chain length. This is supported by the analytical model and present simulation results, leading to predict the optimal chemical structure for better thermal insulation.
INTRODUCTION

Performance improvement of thermal insulation materials used in building and refrigeration units is becoming increasingly important for energy saving\(^1\)\(^-\)\(^6\). The thermal insulator generally takes a highly porous structure composed of low thermal conductivity materials such as silica in order to suppress the solid heat conduction. The vacuum insulated panel (VIP) is a form of thermal insulator consisting of such porous core media depressurized in a sealing material. As the gas heat transfer is eliminated, VIP can realize low thermal conductivity less than 10 mW/m/K\(^7\)\(^-\)\(^11\). Hence, for applications that require extremely low thermal conductivity, development of advanced materials for VIP with better performance, productivity, and fabrication cost effectiveness is important. Since the performance of VIP generally degrades by ageing that gradually lowers the vacuum, nanoparticle-based porous materials are often used for VIP for their relatively robust performance against the gradual loss of vacuum\(^7\)\(^-\)\(^11\). Among the nanoparticle-based thermal insulator, aerogels have been extensively studied, and there are theoretical and experimental reports on the synthesis and physical properties\(^12\)\(^-\)\(^16\). However, since the wet fabrication process for aerogels generally requires supercritical drying that is not suited for production of large-scale materials, simple porous compacts fabricated by dry stamping process are preferable for industrial applications. There, the porous fumed silica nanocomposite (SNC)\(^17\)\(^-\)\(^20\) is known to be an appropriate material for VIP because it also shows excellent thermal insulation under vacuum condition and can be simply fabricated by stamping fumed silica nanoparticles (SNP) in dry condition with a small amount of fibers for reinforcement.

The overall thermal conductivity \((K_m)\) of SNCs is determined by summation of the effective thermal conductivities by solid heat conduction\((K_s)\), gas heat conduction\((K_g)\), and radiative heat transfer \((K_r)\)\(^21\)\(^-\)\(^22\). Here, \(K_m\) in VIP can be approximated by \(K_m=K_s+K_r\) due to negligible
contribution of $K_g$. $K_r$ can be reduced by adding an opacifier with strong optical absorption in the infrared region such as TiO$_2$, SiC, and carbon nanomaterials$^{20,23-25}$. Thus, for further reduction of $K_m$ in vacuum condition, the important challenge is to suppress $K_s$, which is dominantly determined by the interfacial thermal conductance (TBC) between SNPs or between SNP and additives at low material density. An increase in $K_m$ depending on the humidity during the material fabrication process has been reported so far even in vacuum condition, and it may originate from the enhancement of TBC caused by trapped water molecules in the SNC$^7$. It has been reported that material fabrication with hydrophilic or hydrophobic SNPs results in the variation in $K_m$ due to the difference of adhesion force between silica and reinforced fibers$^{19}$. On the other hand, there are several experimental reports showing that the surface functionalization strongly enhances the TBC between solids due to the formation of covalent bonding network at the interface$^{26-28}$. Although these past experimental results support that surface chemical modification is important for the thermal insulation performance, the underlying mechanism has not been clarified yet. Therefore, here we apply a wide variety of surface chemical modifications to SNPs (silanized SNP, SSNP) by a dry silane coupling method$^{29-32}$, measure the $K_m$ of SNC fabricated with the SSNPs (silanized SNC, SSNC) by steady-state heat flux method$^{33}$, and investigate the detailed impact of surface chemical modification on TBC between SNPs from the measured variation in $K_m$.

MATERIAL PREPARATION

SSNPs are prepared by following silane coupling method in dry condition$^{31,32}$. After cleaning the commercial SNPs (CAB-O-SIL® H-300, Cabot Corporation, average diameter, $d_{\text{ave}}$=7 nm) by an UV ozone cleaner for 10 min, the SNPs and a reservoir including 0.2 – 0.3 ml silane coupling reagent are sealed with a Teflon container under N$_2$ condition. Then, the container is
annealed at 150 °C in a muffle furnace to evaporate the chemicals inside and left for 2 hours to complete the reaction of evaporated chemicals with hydroxide (-OH) groups terminated on the surface of SNPs. In this study, we use 5 types of silane coupling reagents that have different numbers ($n$) of liner hydrocarbon (-CH$_3$) groups with 3 reaction sites (-SiOCH$_3$):
methyltrimethoxy silane (MTMS, $n=0$), propyltrimethoxy silane (PTMS, $n=2$), hexyltrimethoxy silane (HTMS, $n=5$), dodecyltrimethoxy silane(DTMS, $n=9$), and octadecyltrimethoxy silane(OTMS, $n=17$). These chemicals are obtained from Tokyo Chemical Industry Co. Further, we use 2 types of silane coupling reagents that have a terminal 3-fluoropropyl group with 2 or 3 reaction sites: 3-fluoropropyl (trimethoxy) silane (FPTMS) and 3-fluoropropyl (dimethoxy) silane (FPDMS). Hexamethyldisilazane (HMDS) is also used to react with one -OH group on the silica surface to form -Si(CH$_3$)$_3$ termination. FPTMS, FPDMS, and HMDS are obtained from Sigma-Aldrich.

The measurement samples are prepared with SNPs (or SSNPs) as follows. After mixing SNPs and 10 wt% biodegradable fibers (Superwool PLUS, Shin-Nippon Thermal Ceramics Corporation) by blender, 4×7 mm wide and 10 mm thick SNC is fabricated by the dry stamping process (see Fig. 1). The samples are used for the thermal conductivity measurement after being annealed at 200 °C for 2 hours under ambient condition. For suppression of the radiative heat transfer, graphite micro particles (GMP, Nippon Graphite Industries,Co.,Ltd., $d_{ave}$=20 μm) are used as an opacifier and the measurement samples are prepared by stamping SNPs with 10 wt% GMPs.

THERMAL CONDUCTIVITY MEASUREMENT
The thermal conductivity of samples is measured by steady-state heat flux method (FOX50 Heat Flow Meter, EKO Instruments). In the steady-state heat flux method\textsuperscript{33}, the sample is sandwiched between heat source and heat sink, whose temperature are controlled electrically by ceramic heater and Peltier element, respectively. The heat flux through the sample and the temperature at both the top and bottom surfaces are measured by equipped sensing element after reaching the steady-state condition, and the thermal conductance is estimated by Fourier’s law \((= q'/\Delta T)\). All samples are measured right after the annealing process. All measurements are performed at room temperature in ambient and vacuum conditions (100 Pa). The thermal conductance is evaluated after confirming that the measurement system had sufficiently reached a steady state by controlling the temperature difference between the top and bottom side to be about 10 °C. For the estimation of the thermal conductivity, the actual sample thickness is evaluated experimentally after mounting the samples onto the measurement system.

**MOLECULAR DYNAMICS SIMULATION**

Non-equilibrium molecular dynamics (NEMD)\textsuperscript{34} simulations are carried out to study the interfacial thermal transport across two hydroxylated or alkysilane-functionalized silica surfaces. Each silica surface is cleaved from \(\alpha\)-quartz crystal to form a \(5.1 \times 5.3 \times 11.0\) nm\(^3\) slab. The interactions inside silica surfaces are modeled by using Tersoff potential.\textsuperscript{35} The force field parameters of hydroxyl groups and alkysilane chains on surface are obtained from Summers et al.,\textsuperscript{36} which is based on the OPLS all-atom model.\textsuperscript{37} The geometric combination rule is applied for the parameters of van-der-Waals interactions between different atoms. The Coulomb interaction is treated using the particle-particle-particle mesh (PPPM) Ewald summation method\textsuperscript{38} for slab geometries.\textsuperscript{39} The equations of motion are integrated with a time step of 0.5 fs.
All the simulations are performed using LAMMPS\textsuperscript{40} molecular dynamics package and visualized with the PyMOL\textsuperscript{41} software.

The system is initially relaxed in the canonical ensemble (NVT) at 300 K using Nose-Hoover\textsuperscript{42,43} thermostat to ensure the system temperature. After the system reaches equilibrium, two 0.5-nm-thick layers at the two ends in the z-direction are fixed to stabilize the system. Then, the NEMD simulations with two thermostatted regions at two ends in the z-directions are performed in the microcanonical (NVE) ensemble to calculate the TBC. The heat source (305 K) and heat sink (295 K) regions are defined as a 1.0-nm-think layer next to the fixed layers. By calculating the heat flux, $J$, between the two thermostatted regions, the value of TBC, $G$, can be evaluated by $G=J/\Delta T$, where $\Delta T$ is the temperature difference at the interface. A 10 ns production run is performed to obtain the steady temperature profile. A linear regression of the temperature profile of each surface is applied to determine the value of $\Delta T$. The data points near the thermostatted regions are excluded from the fitting procedure.

**Figure 1.** (a) Schematics of sample fabrication procedure and representative topographic images of SNCs used in present study. The left-bottom figure shows a transmission electron microscope
image of SNPs. The right top and bottom images show an optical and scanning electron microscope (SEM) images of SNCs, respectively. The white arrow in the SEM image indicates a biodegradable fiber mixed in SNCs. (b) Thermal conductivity of SNCs fabricated in present study as a function of the material density. Red circles and blue squares represent the measurement data taken in air and vacuum condition, respectively. Dashed lines correspond to the average thermal conductivity within the density of 0.19–0.21 g/cm³.

**Figure 2.** Schematics of surface silanization of SNPs, sample fabrication procedure of SSNCs, and structure of chemicals used in present study.

**RESULTS AND DISCUSSION**

**Figure 1** shows representative topographic images of SNCs fabricated by stamping SNPs with biodegradable fibers and density dependence of the $K_m$ measured in air and in vacuum condition. $K_m$ of a porous structure usually exhibits a minimum value at optimal material density because $K_g$ and $K_r$ increase as the density becomes smaller. As shown in **Fig. 1(b)**, $K_m$ of SNC gives an average value ($K_{0,ave}$) of about 20 mW/m/K in air and about 9 mW/m/K in vacuum around the density of 0.2 g/cm³. While appropriate mechanical strength is further required for the experiments, the sample has been sufficiently reinforced so that the material can be handled by adding biodegradable fibers at 0.2 g/cm³. In present experiments, as there is no significant
change in $K_m$ with the moderate variation of fiber concentrations, the fibers play minor role in the thermal conductivity. Further, no specific changes are observed in the topographic image of SSNC after the surface modification of SNPs. Hence, we have confirmed that the $K_s$ is solely dominated by SNPs.

Now that we have confirmed that the $K_s$ is not so sensitive to the density around the optimal value of 0.2 g/cm$^3$ and since the purpose of the current work is to identify the dependence of $K_m$ on types of surface functionalizing chemical, we adjust the density of the samples discussed hereafter to be in the range of 0.19 to 0.21 g/cm$^3$. For the same reason, we present the results in terms of the change ratio ($K_m/K_{0,ave}$) of samples to the reference unmodified SNCs to focus on the variation of surface functionalization effect. As shown in Fig. 2, we prepare SSNPs using 6 types of different chemicals, and the variation in the $K_m$ of SSNCs are measured experimentally.

![Figure 3](image-url)  

**Figure 3.** Variation in the thermal conductivity ($K_m$) of SSNCs. (a) and (b) show the change ratio ($K_m/K_{0,ave}$) as a function of the chain length ($n$) of terminated $-(\text{CH}_2)_n\text{CH}_3$ groups modifying the SNP surface, where $K_{0,ave}$ is average thermal conductivity of SNC at the density of 0.19-0.21 g/cm$^3$. The error bars shown in each data point originate from the uncertainties caused by present steady-state heat flux measurements.
Figure 3 shows the change ratio \( \frac{K_m}{K_{0,ave}} \) of the thermal conductivity of SSNCs with variation of the chain length of chemicals, \((\text{CH}_3\text{O})_3\text{Si} (\text{CH}_2)_n\text{CH}_3\), used for surface modification. As shown in Fig. 3(a), only small variations (<10%) are seen under atmospheric condition. However, Figure 3(b) indicates that the surface modification gives a large variation in \( K_m \) under vacuum condition, particularly with shorter silane coupling reagents \((n<5)\). The maximum change ratio is about 20–30% with PTMS \((n=2)\), where the corresponding thermal conductivity is 6–7 mW/m/K. Furthermore, \( K_m \) increases as the terminal chain of chemicals becomes longer.

Although previous reports have mentioned the strong enhancement in TBC through the thiol-based covalent bonding network\(^{26-27}\), present surface functionalization does not form covalent bond between SNPs. Thus, the observed increase in \( K_m \) is caused by different physical phenomena, and these results indicate that the surface modification of SNPs with \((\text{OCH}_3)_3\text{Si} (\text{CH}_2)_n\text{CH}_3\) modulates the TBC between SNPs, depending on the alkyl chain length. The surface modification with HMDS shows about 5–10% suppression of \( K_m \). HMDS is not silane coupling reagent but replaces -OH groups with -Si(CH\(_3\))\(_3\) on the surface. While the measured variation in \( K_m \) is slightly larger than the results with MPTS, which forms -SiCH\(_3\) on the surface, the variation in \( K_m \) is smaller compared with longer silane coupling reagents. As shown in Fig.2, terminal -OH groups on SNP surface can form a stable hydrogen bond with trapped water molecules inside SNCs. Since these modifications make the surface of SNPs hydrophobic, the results suggest that the hydrogen bonding may be the key element that enhances TBC between SNPs. The replaced terminal groups can inhibit the formation of hydrogen bonds and eliminate the trapped water molecules from SSNCs. The -Si(\(\text{OCH}_3\))\(_3\) groups in silane coupling reagents turn to silanol groups (-Si(OH))\(_3\) by hydrolysis reaction and the silanol groups are highly reactive with the -OH groups on the surface of SNPs through
dehydration reaction. As these chemical reactions create a stable covalent bond network on the surface, the larger number of reaction sites in a silane coupling reagent results in a higher surface coverage that makes the surface more hydrophobic. This gives rise to the larger suppression effect of $K_m$ observed when the SNPs are modified with silane coupling reagents.

Figure 4. Variation in the thermal conductivity ($K_m$) of SSNCs by surface silanization with graphite opacifier. (a) Summary of material fabrication procedure and present experimental results. (b) The change ratio ($K_m / K_{0,ave}$) of thermal conductivity in air and vacuum condition with variation of chemicals used for surface silanization.

To further investigate the suppression effect in $K_m$, SNC and SSNC are fabricated with an addition of 10 wt% GMPs as an opacifier to reduce the $K_t$ simultaneously (see Fig. 4(a)). Figure 4(b) shows the change ratio of $K_m$ including the infrared opacifier with variation of chemicals. The SNC with GMPs shows 25–35 % suppression in $K_m$ compared with the sample without GMPs in vacuum, whereas no variation is seen in air. The SSNCs with GMPs show larger suppression effect ranging from 40 to 50 % in vacuum with FPTMS, corresponding to thermal conductivity of 4–5 mW/m/K. The experimental results indicate that the surface functionalization is effective strategy for further suppression of $K_m$ with infrared opacifiers.
Among the samples, the difference in the measured values between FPTMS and PTMS silanization indicates that a 3-fluoropropyl group is more effective for the suppression of $K_s$.

From the comparison of the results between FPDMS and FPTMS, whose only difference is the number of reaction sites in the chemical structure, the silane coupling reagent with 3 reactive sites give rise to larger suppression of $K_m$. It is considered that all these findings originate from differences in surface hydrophobicity of SNPs controlled by the chemicals.

![Figure 5](image_url)

**Figure 5.** (a) Thermal conductivity of SNCs for different volume fractions and the theoretical curve fitted by the theoretical model as reported previously$^{22}$. (b) Theoretical contribution of solid, gas, and radiative heat transfer to the overall thermal conductivity in air and vacuum condition as a function of the volume fraction.

We adopt an analytical heat transfer model to gain more microscopic understanding in the experimental results. The details of the model are described in our previous report, where we have validated that the open cell based analytical model can explain well the overall thermal conduction in highly porous nanostructures$^{22}$. In short, the porous media is simply modeled as a cubic lattice structure and a quarter of the cube is defined as a single unit cell in the theoretical model (see Fig. 5(a))$^{44}$, and the overall thermal conductivity is written by $K_{\text{framework}} + K_r$, where
$K_{\text{framework}}$ is structural contribution of the thermal conductivity including $K_g$. Then, $K_{\text{framework}}$ is given by

$$K_{\text{framework}} = \frac{4\kappa_{\text{rod}}^t t^2 + K_g (L - 2t)^2}{L^2} + \frac{4\kappa_{\text{rod}}^t K_g t^2 + K_g (L - 2t) t}{2LK_g t + L\kappa_{\text{rod}}^t (L - 2t)}$$  \hspace{1cm} (1)

where $L$, $t$, and $\kappa_{\text{rod}}$ are edge length, half of the frame thickness, and thermal conductivity of the SNP rod, respectively. $K_g$ is a proportion of the gas heat conduction given by the commonly used Kaganer model$^{45,46}$:

$$K_g = \frac{\kappa_{g0}}{1 + 2\beta \Lambda/D}$$  \hspace{1cm} (2)

where $\kappa_{g0} (= 0.026 \text{ W/m/K})$, $\beta$, and $D$ are the thermal conductivity of the gas in free space, a coefficient dependent on the accommodation coefficient and the adiabatic gas coefficient, and the pore size estimated by the volume fraction of the material, respectively. $\Lambda (= k_BT / \sqrt{2\pi d_g^2} p)$ is the mean free path of gas molecules, where $k_B$, $T$, $d_g$, and $p$ are the Boltzmann constant, the temperature, the gas number density, and the pressure, respectively. The value of mean free path is $1.09 \times 10^{-7}$ and $1.1 \times 10^{-4}$ m in air and vacuum condition (=100 Pa), respectively. The proportion of the radiation heat transfer is given by$^{8,2,24,47-50}$

$$K_r = \frac{16\sigma T^3}{3C (1 - \Pi)^f/L}$$  \hspace{1cm} (3)

where $\sigma$ is the Stefan-Boltzmann constant, and $C$ and $f$ are the fitting parameters related to the material property. The $\Pi (= 16(t/L)^3 - 12(t/L)^2 + 1)$ is a porosity of the material calculated from
the density of silica (2.65 g/cm$^3$) and of prepared SNCs that has been determined experimentally. As shown in Fig. 5(a), the quantitative contributions of solid, gas, and radiation heat transfer in $K_m$ can be estimated theoretically by dual fitting (1)–(3) to the density dependent experimental data measured in air and vacuum conditions with 7 unknown parameters ($\kappa_{\text{rod}}$, $\beta_{\text{air}}$, $\beta_{\text{vac}}$, $f_{\text{air}}$, $f_{\text{vac}}$, $C_{\text{air}}$, and $C_{\text{vac}}$). The horizontal axis represents the volume fraction ($V_i$) of samples estimated by the material density ($V_i$=0.075 when the density is 0.2 g/cm$^3$). Figure 5(b) indicates the theoretical proportions given by the fitted parameters ($\kappa_{\text{rod}}$=0.185, $\beta_{\text{air}}$ =0.242, $\beta_{\text{vac}}$ = 0.067, $f_{\text{air}}$=1.98$\times$10$^{-1}$ $f_{\text{vac}}$=1.65$\times$10$^{-1}$ $C_{\text{air}}$=2.2$\times$10$^{-1}$, and $C_{\text{vac}}$=2.71$\times$10$^{-4}$). This analysis suggests that the $K_m$ is dominated by $K_g$ and the contribution of $K_r$ is much smaller in ambient environment, whereas $K_r$ contributes to about 4 mW/m/K in case of vacuum at $V_i$=0.075. The difference of the proportion in atmospheric and vacuum condition reflects the disparate controlling mode for the heat transfer$^{22}$. The analytical results are in good agreement with our present experimental results that the addition of infrared opacifiers to SNCs gives 30–40% reduction in the $K_m$ in only vacuum condition. Since the thermal conductivity of solid framework is formed by serially and alternatingly connecting silica with internal thermal conductivity of 1.38 W/m/K and interface with the TBC, the theoretical variation of $\kappa_{\text{rod}}$ can be estimated as a function of TBC and contact area ($A_c$) between SNPs (see Fig.6(a)). The reduction of $\kappa_{\text{rod}}$ from 0.185 to 0.135 W/m/K gives rise to the measured 20–30% suppression in $K_m$ with the material density of 0.2 g/cm$^3$. The reduction of $\kappa_{\text{rod}}$ is realized with suppression of TBC to be about 50–100 MW/m$^2$K when $A_c$=6–10 nm$^2$. 
Figure 6. (a) Thermal conductivity of SNP frameworks ($\kappa_{\text{rod}}$) as a function of the thermal boundary conductance and contact area ($A_c$) between SNPs. (b) NEMD simulation results of theoretical thermal boundary conductance between silanized silica as a function of chain length ($n$) of $-(\text{CH}_2)_n\text{CH}_3$ groups on the silica surface.

To further deepen the discussion, a silica-silica interface is modeled with terminal linear hydrocarbon groups with different chain lengths. The variation of TBC through the interface are calculated by NEMD simulations. The simulation results in Fig. 6(b) show that the calculated TBC between SSNPs tends to increase as the terminal $-\text{Si}(\text{CH}_2)_n\text{CH}_3$ groups implemented on the silica surface become longer. The number of vibration modes of the surface terminal group increases as the molecular weight of functionalized chemicals become larger, and the increase in the overlap of phonon density of state at surface may result in the enhancement of the interfacial phonon transmittance at the interface. This simulation results qualitatively agrees with our experimental results shown in Fig. 3(b) that $K_m$ increases as the terminal groups become longer in the range of $n>2$ under vacuum condition. In addition, while the analytical model suggests that the 20–30% suppression in $K_m$ measured for the chain length between $n=2$ and $n=9$ result from about 50–100 MW/m$^2$K variation in the TBC, the corresponding variation of TBC of about 100
MW/m²K calculated from the NEMD simulation is consistent. Therefore, these simulation results can qualitatively explain our present experimental findings. The observed large suppression in $K_m$ is due to the surface hydrophobization that causes a disruption of hydrogen bond network, and the subsequent increase in $K_m$ is due to the enhancement of TBC that originate from an increase in phonon transport between silanized surfaces.

CONCLUSIONS

In this study, we target thermal transport properties of porous silica nanocomposite fabricated by dry-stamping process for the application of VIP and demonstrate the systematic surface functionalization to enhance thermal insulation. The surface chemical modification causes a large suppression in $K_m$ (up to 30%) that originates from the elimination of the hydrogen bond network formed by trapped water molecules and has a synergistic effect (up to 55%) with a suppression of radiative heat transfer by addition of infrared opacifiers in vacuum condition. We should note that the surface functionalization is mainly effective under vacuum condition due to neglectable contribution of large $K_g$. The present results predict an optimal chemical structure for better thermal insulation. While surface hydrophobization is effective for the reduction of TBC, the interfacial phonon transport also changes at the same time depending on the chemicals to be modified, which is closely related to the overlapped magnitude of the phonon density of state. Thus, lower molecular weight chemicals that show higher hydrophobicity may be suitable for better suppression of $K_m$. Furthermore, fabrication of SSNC consisting of SSNP mixture functionalized with different types of chemicals may be next strategy for the management of interfacial phonon transport for better thermal insulation.
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NOTES

The authors declare no competing financial interest.

ABBREVIATIONS

VIP (vacuum insulated panel), TBC(Thermal boundary conductance), SNP(fumed silica nanoparticle), SSNP(silanized fumed silica nanoparticle), SNC(fumed silica nanocomposite), SSNC(silanized fumed silica nanocomposite), GMP(graphite microparticle), MTMS (methyltrimethoxy silane) PTMS(propyltrimthoxy silane), HTMS(hexyltrimethoxy silane), DTMS(dodecytrimethoxy silane), OTMS(octadecytrimethoxy silane). FPTMS(3-fluoropropyl (trimethoxy) silane), FPDMS(3-fluoropropyl (dimethoxy) silane). HMDS (Hexamethyldisilazane).

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