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Thermal Performance of a Wire-Mesh/Hollow-Glass-Sphere Composite Structure

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An experimental investigation exploring the use of a wire-screen-mesh/hollow-glass-microsphere combination as a thermal insulation media was conducted with three primary variables. These included the number of wire-mesh layers, the size of microsphere filler material, and temperature range. The test facility used included vertically stacked samples that were thermally and mechanically controlled (e.g., via gas bellows that controlled its vertical movement). From the temperature profile in the upper and lower samples, the value of the effective thermal conductivity was determined with use of the Fourier law of heat conduction. The number of screen mesh layers investigated were two, four, six, and eight, with each separated by a metallic liner. The filler materials included air and S15, S35, and S60HS hollow-glass microspheres tested at temperatures of 27, 57, 93, and 127°C with an interface pressure of 138 kPa (20 psi). The experimental results indicated that the number of layers was the primary factor in determining the effective thermal conductivity value and thus the structure's insulation effectiveness. Increasing the number of wire-mesh layers resulted in a corresponding increase in effective thermal conductivity, whereas changes in temperature had negligible effect. The effective thermal conductivity values for the proposed structure ranged from 0.22 to 0.65 W/m-K, the lowest was for the two-layer case with air as filler material. Wire-screen-mesh insulation with air in the interstices leads to improved insulation, but the use of hollow-glass microspheres does not improve the insulation capabilities.

Nomenclature

k	=	thermal conductivity, W/m-°C
q''	=	heat flux, W/m^2
T	=	temperature, °C
t	=	thickness of insulation, m
U,	=	overall thermal conductance, W/m^{2-}°C
ΔT	=	temperature difference between upper and lower surfaces of the specimen, °C

Subscript

eff	=	effective parameter

Superscript

*	=	properties/values at the interface

Introduction

FUNCTIONAL requirements for thermal insulation are highly dependent on application and a novel thermal insulation must demonstrate, given identical conditions for existing technologies, performance at a superior level. However, quantifiable measurements of insulation thermal, chemical and structural properties serve as a means by which the user may select an appropriate insulation. Most insulation materials chosen for commercial applications derive their insulating properties from low thermal conductivity, which are primarily due to air trapped within the pores of the insulation. Air is a poor conductor of thermal energy; however, gap and/or pore sizes beyond a certain limit may allow heat transfer through convection and/or radiation.

In the development of new insulation materials one surveys existing materials and attempts a combination of materials which may, when combined, potentially have a more desirable thermal performance. One potential combination is that of a metallic-wire-screen mesh with a separator (e.g., metallic liner) with glass microspheres, as shown in Fig. 1 without glass spheres. A metal-screen mesh has qualities similar to other thermal insulations as far as its ability to trap air within its mesh space.

This is achieved by using metallic sheets or liners separating each wire-mesh layer and then selecting mesh sizes with parameters that yield a Rayleigh number less than the critical value. Hollow-glass microspheres, also termed microballoons, find their use as lightweight fillers in composites such as foams, concretes, paints, or plasters. Despite having a higher thermal conductivity than air, the microsphere renders the trapped gas in its hollow cavity as stagnant, which in turn limits convective heat transfer. Thus, the addition of hollow-glass microspheres in the air gaps would be in an attempt to reduce the phonon–phonon mean free path for thermal conduction, thereby reducing heat transfer.

Evidence of the use of metallic-wire mesh as a conduction barrier, whether residentially or industrially, has been sparse and most applications relate to use as a damping medium [1], heat exchanger material [2], packing element in solar air heaters [3], and for structural reinforcement [4]. In the earliest known study of wire-mesh media, Rayleigh [5] proposed a model predicting the effective thermal conductivity of a single layer of wire mesh. By introducing multiple layers, Hsu et al. [6] demonstrated the Rayleigh approach neglected to include the contact conditions between wires and other surfaces. In a related investigation, Alexander [7] empirically correlated thermal conductivities of layered sintered wire screens saturated with water and air. Van Sant and Malet [8] experimentally determined the effective thermal conductivity of 100-mesh stainless steel wire screen along with copper screens saturated with water, CH_3OH, CCl_3F, or air. Many years later, Chang [9] compared Alexander's correlation with data from Van Sant and Malet [8], finding significant overprediction of effective thermal conductivity.

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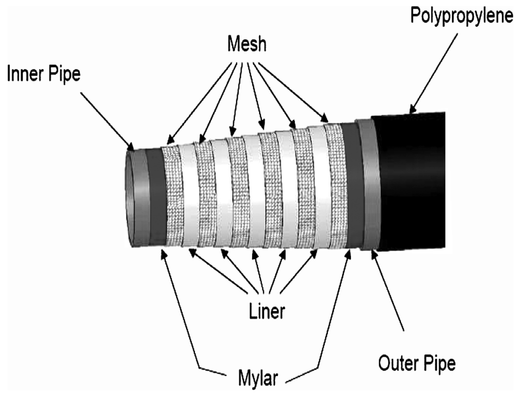

Fig. 1 Schematic of a pipeline multilayer mesh and liner insulation system.

By taking a different approach, Chang [9] defined screens as rectangular cross-sectional segments to mathematically model thermal resistances in series and parallel of a particular unit cell. Contact conditions between metal segments were considered; however, prediction was only found to correlate reasonably well when the ratio of thermal conductivities was between 25 and 160 for specific conditions.

Li and Peterson [10], in a combined experimental and theoretical study of sintered wire screens, critically reviewed existing models and proposed a new theoretical model to determine effective thermal conductivity taking into account contact conditions between wires. Validity of the proposed model was confirmed experimentally by determining the effective thermal conductivity in the direction normal to the screen mesh for a single-layer, inline, and staggered multilayer structures, to be between 4.0 to 25% and 6.0 to 35% of the metal thermal conductivity value, respectively. Actual values depended upon a geometrical parameter and the physical structure, with contact conditions between wires crucial to determining the magnitude of effective thermal conductivity. This provides a basis for the current investigation, since it has been demonstrated that metallic-wire-mesh configurations greatly reduce the effective thermal conductivity when compared with the bulk metal.

Suppose the multiple layers of wire mesh are not stacked consecutively, but a solid barrier is inserted between each layer of mesh. This added element limits the movement of air, and thus convective heat transfer, although the degree to which this will impact the resulting effective thermal conductivity remains to be determined. In one particular instance [11], a metallic wire mesh was used as pipe insulation with promising results. The experimental study consisted of a simulated coaxial pipe fabricated from P110-4140 steel with a stainless steel wire screen as the interstitial insulation material inserted at the annulus. Finally, in the most current study on wire-screen insulation Kim [12] developed an analytical model that includes both micro- and macrocontact resistances and fluid gap resistance applied to a single-layer screen mesh interstitially insulated coaxial pipe. The model showed good agreement with experimental data with some underprediction for low interface pressures at approximately 1 atm. This model may be easily adapted to the proposed wire-mesh insulation containing multiple layers and inclusion of a liner material.

Unlike metal-wire-screen mesh, glass microspheres have long been considered for insulation purposes, in particular, for cryogenic applications. In some cases, microsphere insulation has replaced classical multilayer super insulations despite being unable to match the latter in thermal properties. This may be attributed to microsphere insulation, which has resistance to compressive forces on the order of 10^6–10^7 Pa (N/m^2), thermal isotropy, ease of application, and good reproducibility of thermal parameters [13]. The use of microsphere insulated pressure vessels for hydrogen storage on vehicles [14], cryogenic liquefaction and storage for potential Mars mission [15], and a novel scheme for hydrogen storage based on glass micro-containers [16] all indicate microspheres as a promising insulation media.

Tien and Cunnington [17] investigated the concept of glass microspheres for cryogenic insulation and found that hollow-glass microspheres provide increased thermal resistance to conduction, while reducing heat capacity and weight, when compared with solid spheres. Heat transfer across tightly packed spheres can be separated into two components, conduction and radiation, with the apparent thermal conductivity being the sum of the respective contributions. It has been shown experimentally by Wawryk et al. [18] that the diameter of the microsphere has a direct effect on the radiation contribution to the thermal conductivity, and the contribution to apparent thermal conductivity was more influential above room temperature.

Some studies have focused on microspheres as additives in order to improve particular properties, resulting in improved densities, heat insulation and sound insulation [19]. Many commercial companies have proposed the addition of microspheres to a resin system, for the purpose of increasing or decreasing thermal conductivity [20]. The thermal properties of most commercially available insulation systems are often overestimated because these properties are not achievable in practice, due to environmental factors and usage outside a controlled laboratory setting. For instance, introducing moisture in the form of water vapor to the pores reduces the effective thermal conductivity of insulations as temperature and moisture content are increased [21]. It is imperative to either prevent moisture penetration or allow for sufficient air circulation to prevent vapor buildup. Furthermore, a metal-based insulation system can be susceptible to corrosion. Here, the choice of materials is crucial in combating degradation, although susceptibility to crevice attacks at the metal-to-metal contact points is never eliminated. Introducing hollow-glass microspheres as filler material may potentially limit initial moisture penetration as compared with air, but once a breach has occurred it will likely remain a permanent problem as a mechanism for correction will be difficult to implement.

Experimental Investigation

An experimental investigation was conducted, at steady-state conductions, to determine whether the use of multiple layers of metallic-wire-screen mesh, each separated by a liner, containing hollow-glass microspheres can enhance overall thermal resistance performance for the configuration shown in Fig. 1. The thermo-physical properties such as effective thermal conductivity and thermal contact conductance were computed for comparisons, in order to determine the effectiveness of the multilayer insulation material. The experimental facility used for this investigation has been used for other such studies and has been extensively described by the present authors (Kim et al. [11], Kim [12], and Marotta and Fletcher [22]); therefore, there is no need to further detail its configuration here. In general, the facility consists of a vertical column composed of an upper and lower heat flux meter with the test sample located between two heat flux meters. A pneumatic loading system with a load cell is used to measure the load on the sample, and a suitable heating and cooling system exist to ensure a uniform heat flux across the sample. The heat flux meters and sample are instrumented with T-type special limits of error thermocouples (uncertainty value $\pm 1°C$) and a radiation shield surrounding the test column. The complete system is housed in a vacuum chamber to ensure a controlled environment for the investigation.

The wire-screen mesh used throughout the investigation was a 316 stainless steel five-mesh wire-cloth plain weave, a very common weave that can be produced quickly and economically while exhibiting high corrosion resistance to salts, acids, and seawater. The choice of five-mesh size was based on prior experiments, revealing it as an optimum size in minimizing heat transfer under a controlled laboratory environment [11]. Here, the parameters of the wire-mesh tested in conjunction with the enclosure resulted in a Rayleigh number far below the critical value for rectangular cavities [12]. Thus, resistance due to viscous forces cannot be overcome by buoyancy forces, thus indicating that there exists no advection within the cavity.

The glass microspheres used were three particular classifications S15, S35, and S60HS. The relevant thermal properties are listed in

Table 1 3M glass bubbles properties of interest

Product code	S15	S35	S60HS
Typical true density, g/cm^3	0.15	0.35	0.6
Thermal conductivity at 21°C, W/m-°C	0.055	0.117	0.2
Crush strength with 90% survival, kPa	2,068	20,684	124,105
Crush strength with 90% survival, psi	300	3,000	18,000

Table 1. All three microspheres are of the same chemical composition (soda lime borosilicate glass) with numeric codes representing the typical true densities of each, with HS as an abbreviation for high strength. Specific testing conditions introduced later were carefully considered so as to not push the materials into extremes, where behavior is not well documented.

The selection of a liner, used as a barrier between each layer of wire mesh, functioning as a trap for the filler materials, was carefully chosen.

Although there are numerous possibilities, depending on the material property, a liner was chosen to match the wire mesh in primary composition. The compatibility of mesh and liner is rather crucial, as a metallic wire mesh paired with a liner exhibiting vastly differing mechanical or thermal properties could possibly lead to degradation and failure. In addition, the selection confirms the validity of a metallic-wire-mesh-based insulation system, which could be made rather difficult in the case where the liner material is already been shown to perform as a thermal insulator. With such considerations in mind, a galvanized steel sheet was chosen for the investigation as the liner material because it was readily available and meets the outlined criteria. Galvanized steel is a widely used material that is well known for its workability, but not particularly for its thermal performance; thus, it should not hinder the validity of possible findings.

A diagram of the overall setup for each sample tested consisting of alternating layers of wire five-mesh and liner housed in a Teflon sample holder with eight layers, as shown in Fig. 2. Addition of hollow-glass microspheres would fill the voids in each wire mesh with each liner separating microspheres between the layers. It is important to note that the shaded area surrounding the wire-mesh layers represents the Teflon sample holder, which acts an insulating medium to the ambient environment and also ensures one-dimensional conduction through the multiple layers and microspheres. The temperature measurements were taken in the axial direction of the two heat flux meters, and thus the upper and lower temperatures of the multilayer structure were computed via a linear regression algorithm. These two temperatures were used to determine the temperature drop across the structure and, subsequently, the overall thermal conductance and effective thermal conductivity.

The numbers of mesh layers investigated were two, four, six, and eight, and filler materials included air and S15, S35, and S60HS hollow-glass microspheres. All possible combinations were evaluated at temperatures of 27, 57, 93, and 127°C. These temperatures represented the temperature at the upper interface between the upper heat flux meter and the test sample. All tests were conducted at an interface pressure of 137 kPa (20.0 psi, 1.40 atm) on the vertical test column. The working environment was air for all tests, but for a few cases, tests were conducted under light vacuum in order to estimate heat losses (10^{-3} torr).

Results and Discussion

The experimental results obtained for the wire-screen-mesh insulation system are presented in terms of a similar system with air in the interstitial gap as a basis for comparison with the multilayered insulation with microspheres in the mesh space. The uncertainty of these experimental results was evaluated using the Kline and McClintock method [23]. All measurements were taken with appropriate uncertainty values in mind, and error bars in all figures note uncertainties in the results. The effective thermal conductivity was calculated from the experimentally computed overall thermal conductance U in Eq. (1):

$$k_{\mathrm{eff}} = U \cdot t \tag{1}$$

where t is the overall thickness of the total structure. The computed effective thermal conductivity for multiple layers of wire-screen-mesh insulation, with air as the filler material as a function of mean interface temperature, is shown in Fig. 3. Increasing the number of wire-mesh layers from two to eight resulted in an increase in the corresponding effective thermal conductivity, although each successive increase becomes less pronounced with more layers. This is obvious, since six and eight layers of wire-screen mesh yielded values that are not statistically different. The results tend to be counterintuitive, since an increase in the number of layers should have resulted in more resistance to heat flow, and thus result in lower thermal conductivity.

A closer examination of the experimental setup provides some insight as to a possible reason. The decrease in temperature for all layers at each specified upper-interface temperature remained relatively constant, suggesting that the average heat flux across the insulation played a key role in determination of effective thermal conductivity.

The average heat flux at a given upper-interface temperature decreased as the number of layers increased, thus when viewed in terms of thermal conductance, more layers means more resistance to heat transfer. The computed thermal conductance for multiple layers of wire-mesh insulation with air as the filler material and overall thickness as a function of the upper-interface temperature are shown

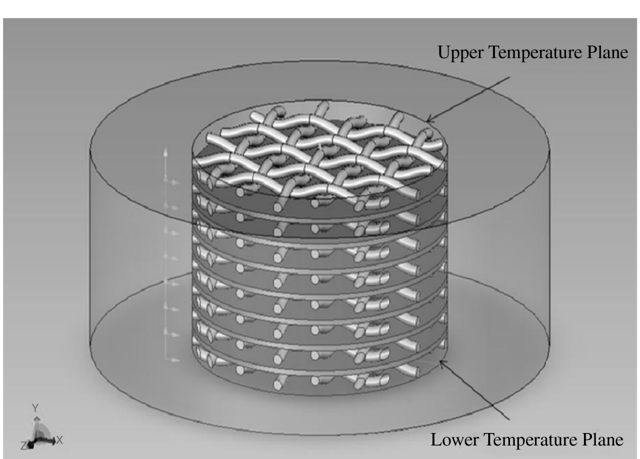

Fig. 2 Diagram of overall setup for each sample tested consisting of alternating layers of wire 5 mesh and liner housed in a Teflon sample holder (eight layers are shown).

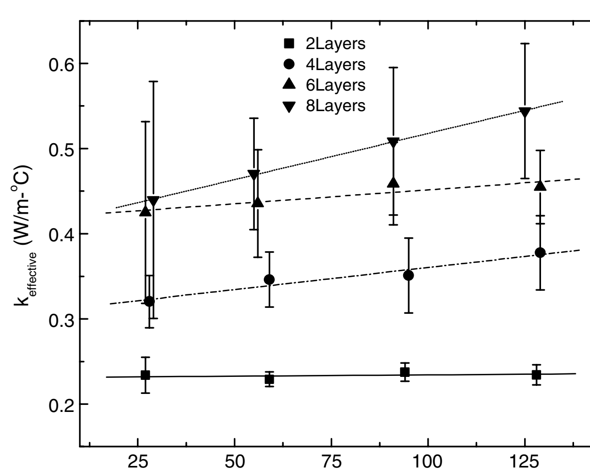

Fig. 3 Effective thermal conductivity of multiple wire-mesh layers as a function of the upper-interface temperature.

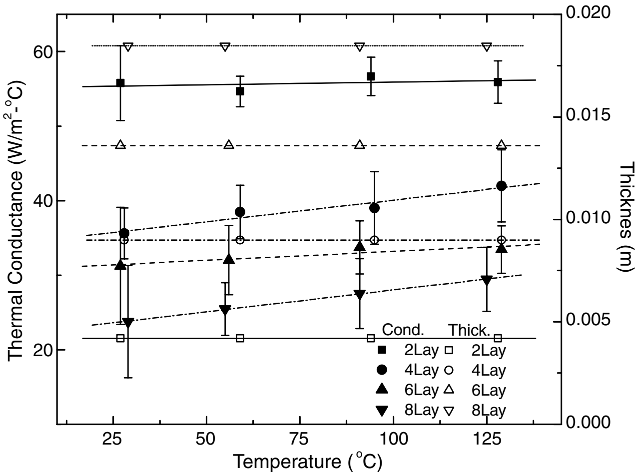

Fig. 4 Thermal conductance and thickness of multiple wire-mesh layers as a function of the upper-interface temperature.

in Fig. 4. This result does not defy conventional wisdom as was implied by only observing the effective thermal conductivity independently. Taking into account the thickness of insulation, the trend reverses, suggesting that increased resistance to heat flow due to the increasing number of layers does not fully counteract the thickness required to achieve it, yielding a net increase in effective thermal conductivity. In examining the role that interface temperature plays on effective thermal conductivity, it is not apparent that any link exists, given the uncertainties involved. In addition, at the maximum temperature of 127°C, the stainless steel wire mesh and galvanized steel sheet are at the lower end of their operating conditions; thus, significant changes in their respective thermal conductivities were not expected.

The computed effective thermal conductivity for multiple layers of wire-mesh insulation with S15 hollow-glass microspheres as the filler material, as a function of the upper-interface temperature, is shown in Fig. 5c. The effective thermal conductivity of multiple layers indicates insignificant changes in the trends observed when compared with Fig. 3. That is, the addition of S15 hollow-glass microsphere did not introduce unforeseen changes in effective thermal conductivity for any particular number of layers.

The degree of separation in effective thermal conductivity between the various layers appears to remain unchanged, with values for two layers remaining significantly lower than the four, six, and eight layers. In addition, there seems to be a slight increase in effective thermal conductivity with increasing temperature, but given the computed uncertainties, the correlation is weak.

The computed effective thermal conductivity for multiple layers of wire-mesh insulation with S35 hollow-glass microspheres as the filler material, as a function of the upper-interface temperature, is shown in Fig. 5b. The calculated effective thermal conductivity hardly differs little when compared with prior cases. Here, looking specifically at the four- and eight-layer cases, there is a statistically significant difference between their respective effective thermal conductivities. This is in stark contrast to the S15 cases, shown in Fig. 5c, where there was noticeable overlap between the four- and eight-layer values.

This suggests that as thermal conductivity of the filler material increases, (thermal conductivity for S35 being two times that for S15), there is a bigger impact as the number of layers increases. Given that effective thermal conductivity already increases with additional layers, the addition of hollow-glass microspheres appears to disproportionately affect the higher number of layers further, reducing its effectiveness as a thermal barrier.

The computed effective thermal conductivity for multiple layers of wire-mesh insulation with S60HS hollow-glass microspheres as the filler material, as a function of the upper-interface temperature, is shown in Fig. 5a. Here, the separation of effective thermal conductivity values between each layer is even more defined than in

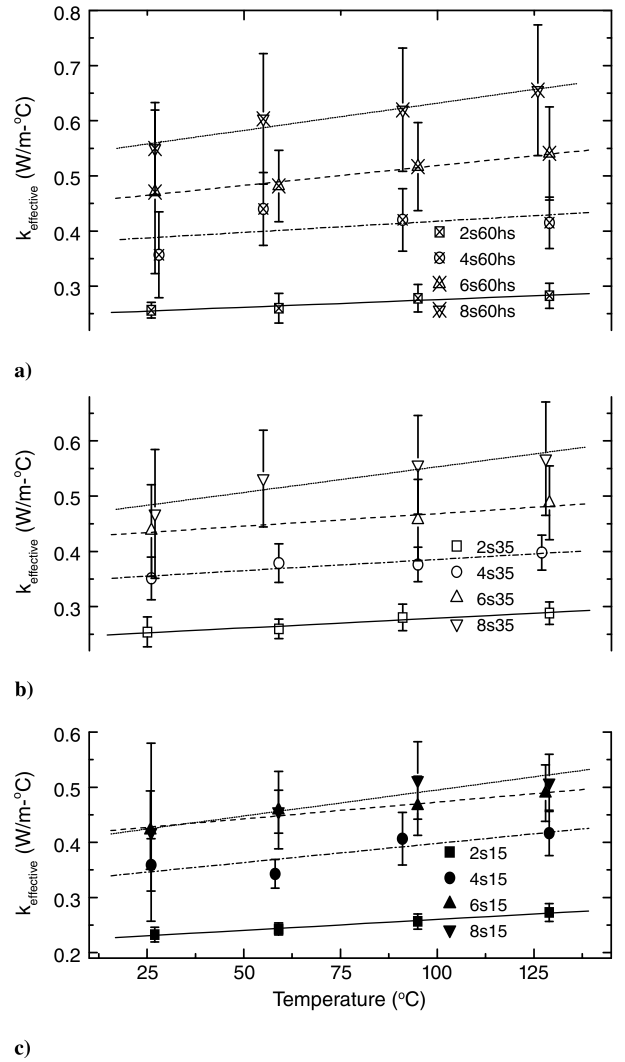

Fig. 5 Effective thermal conductivity of multiple wire-mesh layers (e.g., 2, 4, 6, and 8 layers), with S15, S35, and S60HS hollow-glass microspheres as filler material as a function of the upper-interface temperature.

previous cases. This confirms the previous hypothesis of disproportional increases in effective thermal conductivity values in higher number of layers with hollow-glass microspheres.

The thermal conductivity of S60HS hollow-glass microspheres is 0.2 W/m-°C, the highest of the hollow microspheres tested, very close to that of the calculated effective thermal conductivity in the two-layer air case. Consequently, it becomes apparent that additional layers with S60HS microspheres will tend to accentuate previous trends found with S15 and S35 microspheres. Therefore, given this development, something must be said as to why fillers disproportionately influence the effective thermal conductivity as more layers are introduced. Observably, increasing the number of layers means increasing the volume of hollow-glass microspheres present, and when viewed in terms of thermal resistance, this explains the phenomena satisfactorily. The increased volume means increased surface area for heat transfer, thereby effectively reducing thermal resistance, an unfortunate outcome for all types of thermal insulation.

Recall that additional layers provided greater thermal resistance; thus, the addition of a larger volume of a filler material with a thermal conductivity higher than that of air acted to reduce the overall thermal resistance. For instance, in the two-layer cases where thermal resistance was already relatively low, the addition of a small volume of hollow-glass microspheres resulted in negligible changes in effective thermal conductivity. Conversely, in the eight-layer cases, the additional volume of filler material significantly altered the thermal resistance by providing significant new conduction paths, with the results clearly seen by significant increases in effective thermal conductivities. In light of this observation, it is inferred that the measured effective thermal conductivity is not a good indicator of thermal resistance for this system. Furthermore, examination into the effect of various sizes of hollow-glass microsphere on each particular number of layers should corroborate this finding.

The following four sections aim to further dissect the possible use of multiple metallic-wire-mesh layers with hollow-glass microspheres as a conduction barrier. Keep in mind from Fig. 3 that two wire-mesh layers with air as filler yielded the lowest effective thermal conductivity values of approximately 0.23–0.24 W/m-°C depending on temperature. The effective thermal conductivity of two wire-mesh layers as a function of the upper-interface temperature with air and S15, S35, and S60HS hollow-glass microspheres as filler materials is shown in Fig. 6d.

The results found in Fig. 6d, although not absolutely conclusive due to the inherent uncertainties, appear to indicate an increase in effective thermal conductivity with the addition of glass microspheres as filler material. This is most clearly seen with the S60HS microspheres, the densest of all the filler materials, where there is a statistically significant increase in effective thermal conductivity when compared with air. This would suggest that synergy is not created when combining wire mesh and glass microspheres, but rather thermal performance as an insulation barrier, as measured by effective thermal conductivity, is adversely affected.

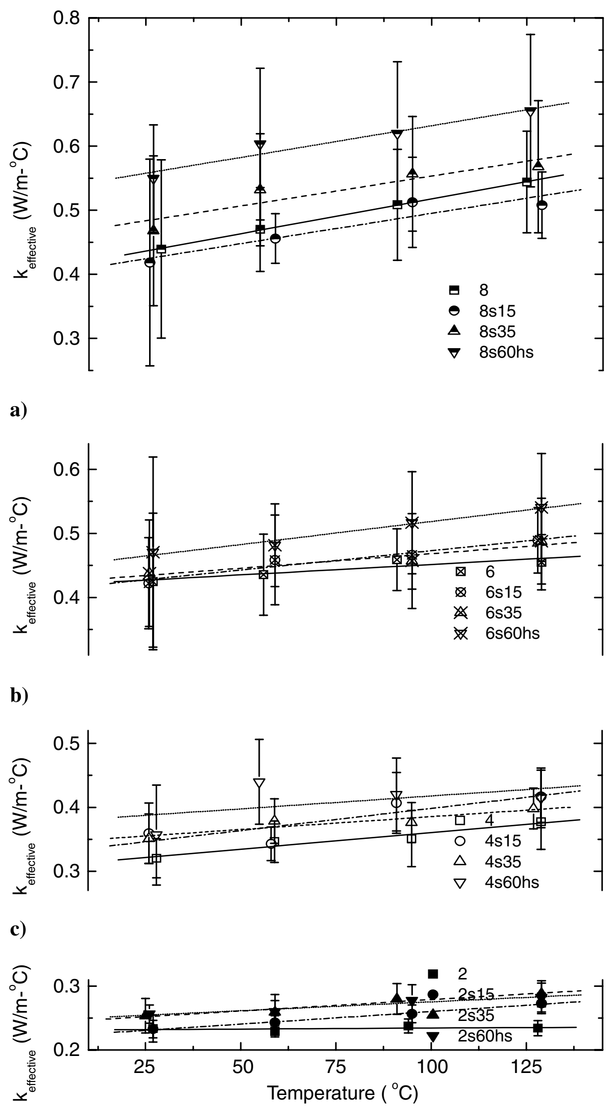

Fig. 6 The effective thermal conductivity for 2, 4, 6 and 8 wire-mesh layers with respective S15, S35, and S60HS glass spheres as a function of the upper-interface temperature under an ambient environment.

It was hypothesized that addition of a filler material such as glass microspheres would reduce conduction within the wire-mesh annular gap, yielding more resistance to heat flow. More specifically, with hollow-glass microspheres the phonon–phonon mean free path for conduction would be reduced significantly when compared with the unfilled air cavity. However, by introducing filler material there exists the possibility that heat transfer by conduction and radiation in the filler material may negate the reduced-bulk air-conduction effect. This is hardly surprising, since thermal conductivity values for all three types of glass microspheres tested were higher than that of air; thus, for these particular instances, any reduction in air conduction is more than offset by increases in heat transfer through the hollow-glass microspheres.

In addition, it appears that effective thermal conductivity of the composite insulation structure is dependent on the temperature at which the test was conducted. This is in slight contrast to the air-filled cases where effective thermal conductivity remained relatively constant with increasing temperature. This behavior might be attributed to the temperature dependence of the thermal conductivity of the hollow-glass microspheres. Nevertheless, the general increase of heat transferred through radiation is an important mode of heat transfer for microspheres above room temperature [13]. In contrast, the wire-screen mesh has a significantly smaller surface area, resulting in negligible documented changes in effective thermal conductivity values.

The effective thermal conductivity of four wire-mesh layers as a function of the upper-interface temperature with air and S15, S35, and S60HS hollow-glass microspheres as filler materials is shown in Fig. 6c. Unlike the previous instance of two layers, the effective thermal conductivity values for four layers for all filler materials tested are statistically equivalent. Even in the case of air, there is significant overlap with the other cases, and thus all that can be gathered for this particular instance is that the addition of glass spheres does not result in significantly measurable changes in effective thermal conductivity values.

With caution, it can be stated that the number of layers of screen wire used largely determines the overall effective thermal conductivity value with filler material having secondary minor effects. This hypothesis should be readily verifiable as the trends in the six- and eight-layer cases are shown. This would tend to suggest that once the number of layers in the insulation design has been selected, then there is very little that can be done to change the overall behavior of the insulation system with these types of filler materials. Also note that there appears to be a slight dependence on temperature, as shown in the two-layer case. However, the correlation is weak at best, given the lack of separation in effective thermal conductivity values for different filler materials.

The effective thermal conductivity of six wire-mesh layers as a function of the upper-interface temperature with air and S15, S35, and S60HS hollow-glass microspheres is shown in Fig. 6b Here, again the overlap in the effective thermal conductivity values reveal very little in terms of differentiating the cases. The most that can be stated is that the addition of glass spheres to six layers of wire mesh does not result in any statistically significant changes in the effective thermal conductivity. This verifies the previously suggested hypothesis that the number of layers plays a far more critical role, having a dominant effect on determining the effective thermal conductivity, with the filler materials having a negligible effect.

Even less can be stated with respect to temperature dependency, since a link is not visibly present. In addition, there appears to be an outlier in the effective thermal conductivity value of the S35 glass-sphere case at appropriately 57°C. The effective thermal conductivity is significantly lower than the present visible trend would suggest. Certainly, there exists many possibilities that may lead to such an appearance, but if no logical reasoning can be found to explain such behavior, then it must be considered an outlier. For at the temperature of 57°C the properties of the materials tested do not exhibit an extreme, and great care was taken to follow a strict protocol in setting up each test run. Thus, the peculiar result deviates from previously seen trends and experimental norms. Further experimentation is required to either verify or disprove its existence.

The effective thermal conductivity of eight wire-mesh layers as a function of the upper-interface temperature with air and S15, S35, and S60HS hollow-glass microspheres as filler materials is shown in Fig. 6a. Not unexpected, with eight layers, the estimated effective thermal conductivity follows similar trends found in the four- and six-layer cases, as shown in Figs. 6b and 6c. As with the four- and six-layer cases, the effective thermal conductivity value of 8 wire-mesh layers, having various filler materials, do not separate themselves sufficiently to infer statistically significant variations. Less significantly, there appears to be a similar upward trend in effective thermal conductivity as a function of temperature, as was seen in previous cases.

The importance of the number of mesh layers over filler material on the overall effective thermal conductivity value can be confirmed by a nondimensional thermal conductivity. The nondimensional effective thermal conductivity was computed as the ratio of the effective thermal conductivity of the number of layers with glass sphere to that without glass spheres. The nondimensional effective thermal conductivity as a function of the upper-interface temperature of S15, S35, and S60HS hollow-glass microspheres is shown in Fig. 7. When the thermal conductivity of the glass microsphere increased from 0.055 W/m-°C (S15) to 0.2 W/m-°C (S60HS), at a temperature of 21°C, its nondimensional effective thermal conductivity value also increased. For instance, in the eight-layer case, a 31% increase in the nondimensional effective thermal conductivity, from 0.959 (with S15) to 1.262 (with S60HS), was computed.

In summary, the use of glass microspheres as filler material for the wire-mesh structure tested appear to have negligible impact on the effective thermal conductivity, given the uncertainties inherent in the experimentation. Even with the assumption that all calculated values represent actual values, uncertainty not included, the addition of hollow-glass microspheres in most of instances increases the effective thermal conductivity value up to 29.5%. Given the results, it can be confidently inferred that air gap conduction was relatively limiting, and thus any attempts in further reduction can only come at the expense of increased heat transfer with hollow-glass microsphere. In effect, the addition of glass microspheres opened up heat transfer paths previously filled with low-conductivity air, which provided very high resistance to conduction. This in turn changed the wire mesh, primarily filled with air, into a wire-mesh and hollow-glass-microsphere system with a significant increase in surface area for conduction heat transfer. With observably less resistance, due to much less air volume, it is no surprise that increases in effective thermal conductivity were seen in many cases. This effect

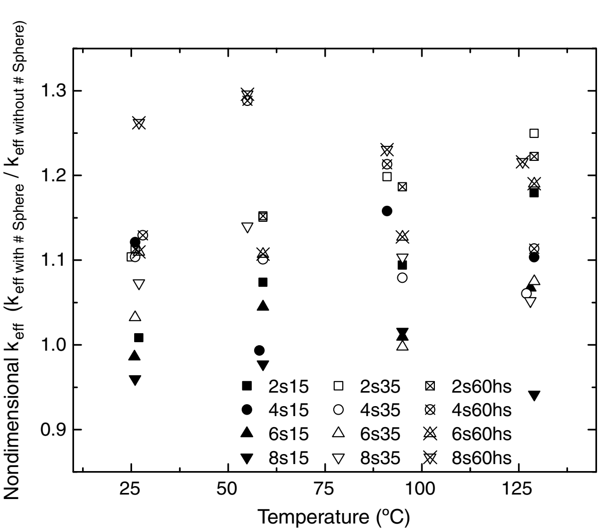

Fig. 7 The nondimensional effective thermal conductivity as a function of the upper-interface temperature.

is most apparent with S60HS hollow-glass microspheres, having thermal conductivity approximately eight times higher than the air configuration. In some instances the effective thermal conductivity of the wire-mesh and S60HS composite structure resulted in a statistically significant increase from the wire-mesh and air structure. These results have the added effect of indirectly reaffirming the choice in size and configuration of wire mesh, which optimizes a low-thermal-conductivity wire material with air gaps that in turn produces limited natural convection (no advection), with thermal conduction as the dominant mode within the gap. Thus, it appears that any attempt to introduce a filler material with thermal conductivity higher than that of air to the tested wire mesh can only adversely influence the underlying effective thermal conductivity. However, in six and eight layers with S15 glass-microsphere cases, up to a 6% effective thermal conductivity decrease was observed. In other words, there is the possibility that given certain mesh sizes, in which natural convection appears dominant to a very high degree, the addition of materials such as glass microsphere may result in a reduction in effective thermal conductivity.

Several experiments were performed without a filler material and under vacuum conditions with the intent of determining heat losses due to radiation. However, the results did not fully converge (e.g., meaning that it did not meet the steady-state criterion for temperature fluctuations, changes of no more than 0.3°C within 1 h), or uncertainties were unacceptable. Thus, the results obtained cannot be compared with those from previous ambient runs because a comparison would be largely incomplete.

Certainly, something must be stated with regard to the heat losses involved that may influence the results shown in prior sections. There are a couple of scenarios that warrant discussion. First, there is the possibility the experimental setup with the Teflon sleeve in combination with a radiation shield, where heat losses were relatively low initially. Thus, drawing a vacuum would have little to no effect on the computed results. Second, the thermal resistance through the metallic-wire-mesh-based insulation tested is significantly lower than that of other possible heat flowpaths, rendering results unchanged even with vacuum. Finally, there is the unlikely prospect that heat losses were significant because the first two scenarios represent inaccurate portrayals of the actual conditions.

Moreover, although the results do not allow for absolute confirmation of any of the scenarios listed, general observation of the vacuum runs do provide some insight. The general trends observed would suggest that heat losses were limited, as the behavior under vacuum did not deviate from the nonvacuum trends.

The wire mesh, despite being shown to have a design consistent with many other insulation materials and structures, by having a large volume of air pockets or voids, could not overcome this bias. The underlying result is that as more layers are introduced, more layers of the liner are introduced, leading to a reversing of the roles initially set forth. That is, the insulation structure became the liner, with wire mesh simply dividing each liner layer instead of vice versa. Thus, in order to develop a competitive thermal insulation structure with multiple layers, all the constituent layers must independently exhibit similar insulating properties. Otherwise, there may be an equalization of thermophysical properties between the constituents, as was seen with the effective thermal conductivity of the wire-mesh and liner composite structure.

The task of determining whether the proposed insulation scheme can be competitive with those currently in service can now be undertaken, given the extensive analysis in previous sections. Shown in Tables 2–4 and Fig. 8 are test parameters and thermal conductivity values for the proposed insulation, along with some conventional insulation materials. If the wire-mesh and hollow-glass-microsphere composite structure is considered purely as a conduction barrier based on thermal conductivity alone, then the thermal performance is noticeably inferior. Even considering the best-performing wire-mesh and hollow-glass-microsphere case, the effective thermal conductivity ranges from 3–10 times that of conventional insulation materials. However, selection of an insulation system is an intricate process based on many factors beyond the scope of this study, with thermal conductivity being merely one component. This will become

Table 2 Test parameters

Consideration	Description
Wire mesh	316 stainless steel five-mesh wire-cloth plain weave, 0.9 mm diam.
Glass microsphere	3M glass bubbles code: S15, S35, and S60HS
Sheet liner	Galvanized steel 24 GA., 0.05 cm thickness
Test sleeve	Machined Teflon cylinder: i.d. 2.54 cm, 1 in.
Upper-interface temperature	27, 57, 93, 127°C
Loading pressure	137.89 kPa, 20 psi
Environment	Ambient, medium vacuum

Table 3 Thermal conductivity of proposed insulation along with some conventional materials at 27°C (300 K)[24]

Material	Thermal conductivity, W/m-°C
Wire mesh with hollow-glass microsphere	0.22–0.65
Wire mesh without hollow-glass microsphere	0.22–0.54
Air	0.0263
Fiber glass	0.032–0.050
Wood wool	0.068
Mineral wool	0.036

Table 4 Thermal conductivity of other conventional insulation materials used in subsea applications at 27°C (300 K) [24]

Material	Thermal conductivity, W/m-°C
Rock wool	0.034–0.041
Polyethylene	0.062
Polyurethane	0.023
Expanded polystyrene	0.035–0.046
Extruded polystyrene	0.039
Aerogel	0.012

more apparent upon considering some advantages and disadvantages associated with the proposed design.

Advantages

The primary advantage in using a metallic-wire-mesh-based insulation system lies in the inherent properties of metals in general. That is, the strength that can be achieved with many alloys make it more structurally sound compared with non-metal-based insulation systems. In particular, superior compressive strengths along with fair insulating properties may have uses as deep sea or underground piping insulation. In addition, high-temperature applications (127–727°C) for thermal insulation become possible (specifically, with ferrous or nickel-based alloys), with some even exhibiting noticeably lower thermal conductivity at higher temperatures.

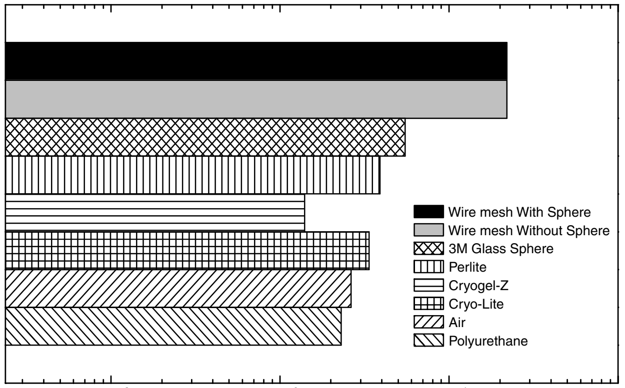

Fig. 8 Thermal conductivity of several conventional materials at 27°C.

There are also the instances where insulations are subject to cyclical thermal loading, whereby thermal expansion of the material(s) becomes critical. Polymeric insulations, in general, tend to be more susceptible to thermal fatigue than are metals, especially given multilayer designs common in today's insulation systems. In addition, polymers being an organic material are more susceptible to combustion then their nonorganic counterparts, thus limiting its use in certain applications where safety is of utmost importance.

Metallic-wire-mesh-based insulation will tend to be sleeker in design, due to weight considerations with potential impact on form and function. For instance, general house appliances could be manufactured with increased space of serviceability without sacrificing efficiency. A thinner insulation would also have increased visual appeal by limiting the space protrusion around pipes and components in heating, ventilation, and air conditioning systems.

Finally, glass microspheres have reduced weight (low density), increased compression strength and high-temperature resistance that make them suitable for aerospace applications. These characteristics can result in an increase in the payload, enhanced structural strength under high loading, and improved insulation performance under extensive thermal stress. When used as an ingredient, such as metal form filler for a layered structure in aircraft construction, mechanical, and thermophysical performance enhancement can be expected.

Disadvantages

The primary concern in the use of the proposed design lies in its thermal performance characteristics, in particular thermal conductivity. A metallic based insulation should exhibit insulating properties approaching their nonmetallic counterparts to be considered viable as a conduction barrier. Should this condition be achieved, then secondary concerns involving insulating system integration and failure modes must be considered.

With respect to the incorporation of wire-mesh-based insulation into existing systems, several hurdles must be solved. Widely accepted insulation schemes have established their superiority through many years of trial and error; thus, the supporting infrastructure exists to install, service, and maintain these insulations. Introduction of new concepts into any established industry requires a great deal of commitment to overcome the inherent skepticism. Consequently, it requires more than superior technology, which at this point cannot be said of wire-mesh/hollow-glass-microsphere composite structure, to supplant existing insulation schemes.

Even working on the assumption that thermal performance of the proposed insulation scheme is on par with existing insulation technologies, the question of economic feasibility must be answered. There exist numerous technological concepts that were never adopted, not because they did not represent superior ideas, but because the required capital structure that was not economically viable. It must be shown that a metallic-wire-mesh-based insulation system can be competitive on a performance-per-cost basis in order to gain market share. This crucial entrepreneurial step involves many risks, which may be deemed unnecessary.

Challenges regarding possible failure modes of a wire-mesh-based insulation are largely unknown, but given the design and materials involved, something can be said about possible degradation mechanisms. In dealing with metals in particular, corrosion can be quite destructive, often leading to eventual failure when accompanied with mechanical loading. Here, material selection is the chief method used in corrosion prevention, whereas design considerations can mute the impact of an electrochemical attack. Stainless steels and galvanized steels come to mind when considering readily available metals with some resistance to corrosion while being economically viable.

Also consider that the presence of moisture in any insulation system will almost always render the insulation less effective by enhancing the heat transferred, while degrading the host structure, whether metal or nonmetal. The mechanisms for degradation may vary, but the outcome is not favorable in any case. Thus, metallic-wire-mesh-based insulations offer negligible improvement in this particular area.

Conclusions

An experimental investigation exploring the use of a wire-mesh/hollow-glass-microsphere combination for use as a thermal insulation was conducted to determine whether this combination would provide a significant improvement in insulation technology. Three primary variables were considered: 1) the number of wire-mesh layers, 2) the size of the microsphere filler material, and 3) temperature range. The test facility used included vertically stacked samples that were thermally and mechanically controlled. The numbers of screen mesh layers investigated were two, four, six, and eight, with each separated by a metallic liner. Gap filler material consisted of air, S15, S35, and S60HS hollow-glass microspheres, each individually tested at temperatures of 27, 57, 93, and 127°C with an interface pressure of 138 kPa (20 psi).

The experimental results indicated that the number of layers used was the primary factor in determining the effective thermal conductivity value. Increasing the number of wire-mesh layers resulted in a corresponding increase in effective thermal conductivity of the insulation, whereas changes in temperature had little to no effect. The effective thermal conductivity values for the proposed insulation structure ranged from 0.22 to 0.65 W/m-K, the lowest of which was for the two-layer case with air as filler material. A wire-mesh insulation with air in the interstices does lead to improved insulation, but the use of hollow-glass microspheres does not improve the insulation capabilities. There is evidence that S15 hollow-glass microspheres do lead to performance in insulation when compared against air, due to its smaller length scale; however, this performance enhancement is no more than 5%.

This experimental investigation suggests some interesting results and recommendations for further investigation. First, it would be interesting to investigate different liner materials to ascertain the thermal impact of such materials. Stainless steel or nonmetallic liners would reduce the thermal conductivity of the total mesh insulation. Additionally, better thermal conductivity/thermal resistance data for commercially available insulation must be obtained in order to provide better comparisons.

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References

[1] Hou, J. F., Bai, H. B., and Li, D. W., "Damping Capacity Measurement of Elastic Porous Wire-Mesh Material in Wide Temperature Range," *Journal of Materials Processing Technology*, Vol. 206, Nos. 1-3, Sept. 2008, pp. 412–418.
doi:10.1016/j.jmatprotec.2007.12.053

[2] Xu, J., Tian, J., Lu, T. J., and Hodson, H. P., "On the Thermal Performance of Wire-Screen Meshes as Heat Exchanger Material," *International Journal of Heat and Mass Transfer*, Vol. 50, Nos. 5–6, March 2007, pp. 1141–1154.
doi:10.1016/j.ijheatmasstransfer.2006.05.044

[3] Mittal, M. K., and Varshney, L., "Optimal Thermohydraulic Performance of a Wire Mesh Packed Solar Air Heater," *Solar Energy*, Vol. 80, No. 9, Sept. 2006, pp. 1112–1120.
doi:10.1016/j.solener.2005.10.004

[4] Riva, P., and Franchi, A., "Behavior of Reinforced Concrete Walls with Welded Wire Mesh Subjected to Cyclic Loading," *ACI Structural Journal*, Vol. 98, No. 3, May 2001, pp. 324–334.

[5] Rayleigh, L., "On the Influence of Obstacles Arranged in Rectangular Order Upon the Properties of a Medium," *Philosophical Magazine*, Vol. 56, 1892, 481–502.

[6] Hsu, C. T., Wong, K. W., and Cheng, P., "Effective Stagnant Thermal Conductivity of Wire Screens," *Journal of Thermophysics and Heat Transfer*, Vol. 10, No. 3, 1996, 542–545.
doi:10.2514/3.825

[7] Alexander, E. G., Jr., "Structure-Property Relationships in Heat Pipe Wicking Materials," Ph.D. Dissertation, Dept. of Chemical Engineering, North Carolina State Univ., Raleigh, NC, 1972.

[8] Van Sant, J. H., and Malet, J. R., "Thermal Conductivity of some Heat Pipe Wicks," *Letters in Heat and Mass Transfer*, Vol. 2, 1975, pp. 199–206.
doi:10.1016/0094-4548(75)90021-1

[9] Chang, W. S., "Porosity and Effective Thermal Conductivity of Wire Screens," *Journal of Heat Transfer*, Vol. 112, No. 1, 1990, pp. 5–9.
doi:10.1115/1.2910365

[10] Li, C., and Peterson, G. P., "The Effective Thermal Conductivity of Wire Screen," *International Journal of Heat and Mass Transfer*, Vol. 49, Nos. 21–22, Oct. 2006, pp. 4095–4105.
doi:10.1016/j.ijheatmasstransfer.2006.03.031

[11] Kim, D., Silva, C., Marotta, E., and Fletcher, L., "Characterization/Modeling of Wire Screen Insulation for Deep-Water Pipes," *Journal of Thermophysics and Heat Transfer*, Vol. 21, No. 1, 2007, pp. 145–152.
doi:10.2514/1.25886

[12] Kim, D. K., "An Analytical and Experimental Investigation for an Interstitial Insulation Technology," Ph.D. Dissertation, Dept. of Mechanical Engineering, Texas A&M Univ., College Station, TX, 2008.

[13] Wawryk, R., and Rafalowicz, J., "Heat Transfer in Microsphere Insulation," *Journal of Thermal Analysis*, Vol. 34, No. 1, Jan. 1988, pp. 249–257.
doi:10.1007/BF01913391

[14] Aceves, S. M., Berry, G. D., and Rambach, G. D., "Insulated Pressure Vessels for Hydrogen Storage on Vehicles," *International Journal of Hydrogen Energy*, Vol. 23, No. 7, July 1998, pp. 583–591.
doi:10.1016/S0360-3199(97)00079-7

[15] Mueller, P., and Durrant, T., "Cryogenic Propellant Liquefaction and Storage for a Precursor to a Human Mars Mission," *Cryogenics*, Vol. 39, No. 12, Dec. 1999, pp. 1021–1028.
doi:10.1016/S0011-2275(99)00107-1

[16] Kohli, D. K., Khardekr, R. K., Singh, R., and Gupta, P. K., "Glass Micro-Container Based Hydrogen Storage Scheme," *International Journal of Hydrogen Energy*, Vol. 33, No. 1, Jan. 2008, pp. 417–422.
doi:10.1016/j.ijhydene.2007.07.044

[17] Tien, C. L., and Cunnington, G. R., "Glass Microsphere Cryogenic Insulation," *Cryogenics*, Vol. 16, No. 10, Oct. 1976, pp. 583–586.
doi:10.1016/0011-2275(76)90187-9

[18] Wawryk, R., Rafalowicz, J., and Balcerek, K., "The Influence of Microsphere Diameter on the Coefficient of Thermal Conductivity of Microsphere Insulation," *Cryogenics*, Vol. 23, No. 8, Aug. 1983, pp. 441–443.
doi:10.1016/0011-2275(83)90215-1

[19] Nakanoshima, K. O."Expandable Microspheres for Weight Reduction in PVC, SBS and EVA," *Additives for Polymers*, Vol. 2003, No. 8, Aug. 2003, pp. 3–4.
doi:10.1016/S0306-3747(03)00805-4

[20] "Microspheres: Thermal Conductivity Report," 3M Specialty Materials Div., St. Paul, MN, June 1998, p. 1.

[21] Ochs, F., Heidemann, W., and Muller-Steinhagen, H., "Effective Thermal Conductivity of Moistened Insulation Materials as a Function of Temperature," *International Journal of Heat and Mass Transfer*, Vol. 51, Nos. 3–4, Feb. 2008, pp. 539–552.
doi:10.1016/j.ijheatmasstransfer.2007.05.005

[22] Marotta, E. E., and Fletcher, L. S., "Thermal Contact Conductance of Selected Polymeric Materials," *Journal of Thermophysics and Heat Transfer*, Vol. 10, No. 2, 1996, pp. 334–342.
doi:10.2514/3.792

[23] Kline, S. J., and McClintock, F. A., "Describing Uncertainties in Single-Sample Experiments," *Mechanical Engineering*, Vol. 75, Jan. 1953, p. 3.

[24] Abdou, A. A., and Budaiwi, I. M., "Comparison of Thermal Conductivity Measurements of Building Insulation Materials Under Various Operating Temperatures," *Journal of Building Physics*, Vol. 29, 2005, pp. 171–184.
doi:10.1177/1744259105056291