EVALUATION OF THE THERMAL PERFORMANCE FOR A WIRE MESH/HOLLOW GLASS MICROSPHERE COMPOSITE STRUCTURE AS A CONDUCTION BARRIER

A Thesis

by

SEAN LI MCKENNA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2008

Major Subject: Mechanical Engineering

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Approved by:

Chair of Committee,	Egidio Marotta
Committee Members,	Debjyoti Banerjee
	Perla Balbuena
Head of Department,	Dennis O'Neal

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ABSTRACT

Evaluation of the Thermal Performance for a Wire Mesh/Hollow Glass Microsphere Composite Structure as a Conduction Barrier. (December 2008)

Sean Li McKenna, B.S., University of Florida

Chair of Advisory Committee: Dr. Egidio Marotta

An experimental investigation exploring the use of wire mesh/hollow glass microsphere combination for use as thermal insulation was conducted with the aim to conclude whether or not it represents a superior insulation technology to those on the market.

Three primary variables, including number of wire mesh layers, filler material, and temperature dependence were studied using an apparatus that was part of L.I.C.H.E.N (LabVIEW Integrated Conduction Heat Experiment Network), a setup whose basic components allow three vertically stacked samples to be thermally and mechanically controlled. Knowing the temperature profile in the upper and lower samples allows for determination of thermal conductivity of the middle material through the use of Fourier's law. The numbers of layers investigated were two, four, six, and eight, with each separated by a metallic liner. The filler materials included air, s15, s35 and s60HS 3M™ hollow glass microspheres. The experiments were conducted at four temperatures of 300, 330, 366, and 400K with an interface pressure of 20 Psi.

The experimental results indicated the “number of layers” used was the primary factor in determining the effective thermal conductivity value. The addition of hollow glass microspheres as filler material resulted in statistically insignificant changes in effective thermal conductivity. Increasing the number of wire mesh layers resulted in a corresponding increase in effective thermal conductivity of the insulation. Changes in temperature had little to no effect on thermal conductivity.

The effective thermal conductivity values for the proposed insulation structure ranged from 0.22 to 0.65 W/m-K, the lowest of which came from the two layer case having air as filler material. The uncertainties associated with the experimental results fell between 10 to 20 percent in all but a few cases. In the best performing cases, when compared with existing insulation technologies, thermal conductivity was approximately 3 to 10 times higher than these methods of insulation. Thus, the proposed insulation scheme with hollow glass-sphere filler material does not represent superior technology, and would be deemed uncompetitive with those readily available in the insulation market.

DEDICATION

To my mother

ACKNOWLEDGEMENTS

I wish to thank all those who assisted in my research ultimately leading to the completion of this thesis. First and foremost Dr. Ed Marotta, my advisor for providing support and guidance through the entire research process. I am also indebted to my friend and colleague Dr. Dong Kim who aided in performing the necessary experiments while consistently providing moral support.

In addition, I would like to thank Mr. Izzy Ramirez for always welcoming me and allowing me the use of various equipments and supplies found in his heat transfer laboratory. Lastly, a special thanks to my committee members, Dr. Banerjee and Dr. Balbuena, for allocating their valuable time to serve on my committee.

NOMENCLATURE

α	Empirical constant found in model [9]
ε	Volumetric porosity
k	Thermal conductivity (W/m-K)
m	Slope associated with linear regression of flux meter (K/m)
q''	Heat flux (W/m^2)
t	Thickness of insulation (m)
ΔT	Temperature difference (K)
T	Temperature (K)
w_R	Uncertainty associated with variable R
x	*x*-coordinate (m)
Subscripts	
eff/effective	Denotes the effective parameter
f	Fluid phase
l	Lower
lower	Denotes properties/values of the lower flux meter
s	Solid phase
u	Upper
upper	Denotes properties/values of the upper flux meter
Superscripts	
*	Denotes properties/values at the interface

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CHAPTER I

INTRODUCTION

What makes a particular thermal insulation more desirable than another is its ability to perform the required task at a cost the customer deems worthwhile. Functional requirements for thermal insulations are highly dependent on the application, but it is apparent that insulations currently in use have demonstrated a capacity to fill present requirements at reasonable costs. Development of novel thermal insulations must demonstrate, given identical conditions to existing technologies, performance at a superior level. Measurement of this performance is somewhat arbitrary and cannot be quantified without error, as ultimately, the individual user or group must decide what is best. However, quantifiable measurements of insulations' thermal, physical, chemical, etc. properties serve as a means by which the user is able to make an informed choice.

Materials chosen for commercial applications derive their insulating properties from low conductivity that is primarily due to air trapped within the pores of the insulation. Air is a poor conductor of heat, but pore sizes beyond a certain limit allow heat transfer through convection and radiation. With this in mind, a foundation is laid for selection of materials or combinations thereof for use as thermal insulation. In development of new insulations, one surveys existing materials available in a vast variety of forms and attempts a combination of materials that, when combined, potentially have a more desirable outcome. One such combination is that of a metallic wire screen mesh and hollow glass microsphere.

This thesis follows the style of *International Journal of Heat and Mass Transfer*.

Metal screen meshes have historically been accessories in holding other block insulations, or served to reinforce cement finishes. However, their use as the main insulating component has not been utilized since metallic materials tend to have conductivity values much larger then their non-metal counterparts. Upon closer examination, a metallic wire mesh does inherently have qualities not unlike other thermal insulations as far as its ability to trap air given some enclosure. This is achieved using a liner separating each wire mesh layer. Also, by selecting mesh sizes with parameters that yield a Raleigh number less than the critical value of 1708[1], advection is eliminated within the cavities. However, the question of whether air trapped within the wire mesh can counteract the relatively free flow of heat through the metallic wire itself remains to be answered.

Hollow glass microspheres, also termed micro-balloons, find their use as lightweight fillers in composites such as foams, concretes, paints or plasters. Their use is primarily to introduce air into an otherwise homogeneous setting in order to aid structural rigidity and thermal properties. Despite having a higher conductivity than air, it succeeds in rendering air stagnant, which in turn limits convective heat transfer. However, as mentioned previously, selection of wire mesh can be such that no advection is present within the enclosed cavities. Thus, addition of hollow glass microspheres filling the air gaps would be an attempt to reduce the "mean free path" of air conduction, thereby reducing heat transfer. It should be noted that the increased thermal resistance by conduction may come at the expense of increased conduction via hollow glass spheres, but it’s hypothesized that due to the hollow nature of the microspheres the net effect should be beneficial to greater thermal resistance.

Determination of relevant insulation parameters to characterize new insulation forms is a concern, as there are countless possibilities if the proposed insulation is investigated for any possible use. However, given the resources available to conduct these experiments, the proposed insulation will only be considered in thermal conduction, meaning for use as a conductive barrier. This imposed limitation yields an investigation that is manageable, yet practical, as results can be readily compared to existing insulations. The main function of a conductive barrier is to reduce the rate of heat transfer via conduction across the medium when compared to no barrier.

Effectiveness of such a barrier can be largely described through Fourier’s law, which states that the rate of heat flux is directly proportional to the temperature gradient, under steady state conditions, with the proportionality constant termed “thermal conductivity”. The proportionality constant is called “effective thermal conductivity” if the medium in question is non-homogenous in material and/or construction. A closely related term called “thermal conductance’, analogous to thermal conductivity with the thickness of the barrier taken into account, may also be used, although comparisons between insulations historically tend to be done on a per unit thickness basis. Thus, effective thermal conductivity plays a significant role in determining the degree of heat loss.

This experimental investigation explored the use of multiple layers of metallic wire-screen mesh, each separated by a liner with hollow glass micro-spheres as filler material, for the purpose of thermal insulation. Thermo-physical properties such as effective thermal conductivity and thermal conductance were measured to determine whether or not this particular insulation scheme is competitive with existing technologies.

CHAPTER II

LITERATURE REVIEW

2.1 Wire screen mesh

Evidence of the use of metallic wire mesh as a conduction barrier, residentially or industrially, has been sparse and unremarkable, at best. Many studies concerning the use of metallic wire mesh have not been specifically for potential insulation-related application, but include uses as a damping medium [2], heat exchanger material [3], packing element in solar air heater [4], and for structural reinforcement [5]. However, an investigation of the available literature reveals valuable insights into possible uses of wire mesh type media for the purpose of insulating.

In the earliest known study of wire mesh type media, Rayleigh [6] proposed a model predicting the effective thermal conductivity of a single layer of wire mesh given in Eq. (2.1). This analytical expression is widely used and has been experimentally confirmed in limited cases. By introducing multiple layers HSu [7] demonstrated the equations' inability to accurately represent the actual state of affairs because contact conditions between wires and other surfaces are not taken into account.

$$k_{eff} = \frac{k_f\left[k_f + k_s - (1-\varepsilon)(k_f - k_s)\right]}{k_f + k_s + (1-\varepsilon)(k_f - k_s)} \tag{2.1}$$

In a related investigation Alexander [8] empirically correlated thermal conductivities of layered sintered wire screens saturated with water and air to be:

$$k_{eff} = k_f (k_s / k_f)^{(1-\varepsilon)^{0.59}} \tag{2.2}$$

Later, Van Sant and Malet [9] experimentally determined the effective thermal conductivity of 100-mesh stainless steel wire screen and with copper screens saturated with water, CH3OH, CCl3F or air. Chang [10] many years later compared Alexander's correlation to data from Van Sant and Malet, finding significant over-predicting of effective thermal conductivity. By taking a different approach, Chang modeled screens as rectangular cross-sectional segments to mathematically model thermal resistances in series and parallel for a particular unit cell. Contact conditions between metal segments were considered and were represented by a parameter, α. However, prediction was only found to correlate reasonably when the ratio k_s / k_f was between 25 to 160 for specific values of α.

Further, Li and Peterson [11] 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 verified experimentally to determine the effective thermal conductivity in the direction normal to the screen mesh, for single layer inline structures and staggered multilayer to be 4-25% and 6.4-35% times of the metal conductivity, 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 as it's been clearly demonstrated that metallic wire mesh configurations greatly reduce the effective thermal conductivity as compared to bulk metal. Suppose the multiple layers of wire mesh are not stacked consecutively, but rather a solid barrier exists between each layer as has been proposed. This added element aims to limit 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 shown.

In one particular instance [12] metallic wire mesh was used as pipe insulation with promising results. The experimental study consisted of a 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 [13] develops an analytical model that includes both micro- and macro-contact 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 under-prediction for low interface pressure around one atmosphere. This model can be easily adapted to the proposed wire mesh insulation containing multiple layers and inclusion of a liner material. Comparison of Kim's model to data collected should reinforce the legitimacy of the experiments performed, as basic trends through modeling should match experimental results.

2.2 Hollow glass microsphere

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 can be attributed to microsphere insulation having 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 [14]. For instance, application of microsphere insulated pressure vessels for hydrogen storage on vehicles showed good thermal performance [15]. In addition, Mueller [16] in examining cryogenic liquefaction and storage, considered critical in a potential human mars mission, indicated microsphere insulation as showing good promise. More recently, Kohli [17] proposed a novel scheme for hydrogen storage based on glass micro-containers exhibiting unique efficiencies while being comparatively safer than large pressure vessels.

Tien and Cunnington [18] investigated the concept of glass microspheres for cryogenic insulation, including characterization of microsphere heat transfer mechanisms with existing experimental data and potential applications. They described microsphere insulations as a special case of porous media. Of particular interest, hollow glass microspheres provide increased thermal resistance to conduction while reducing heat capacity and weight when compared to 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 [19] that the microsphere diameter has a direct effect on the radiation contribution to the thermal conductivity. Moreover, the radiation contribution to the apparent thermal conductivity above room temperature was more influential.

Some studies have focused on microspheres as additives in order to improve particular properties. In particular, Kaneka Corp of Osaka and Dainichiseika Color & Chemical Mfg. Co. of Tokyo, in a joint venture, have developed microsphere additive technology for expanding PVC, SBS, and EVA resins [20]. With the outcome resulting in improved part densities, heat insulation and sound insulation. The addition of microspheres to a resin system has long been promoted by 3M™, an industry leader in the manufacture and sale of glass microspheres. In particular, for the purpose of increasing or decreasing thermal conductivity, with applications including the following [21]:

- Potting compounds – protecting components from environmental heat.
- Floor tiles with a feeling of warmth.
- Insulating pipe wrap to decrease heat loss.
- Refractory brick in furnaces for heat retention.
- Syntactic foam insulation.
- Cast polyester products with the warm feel of wood.

2.3 Other considerations

Commercially available insulations often overestimate their capabilities. Quoted values of properties, such as thermal conductivity, are in practice not achievable 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 [22]. It is imperative to either prevent moisture penetration or allow for sufficient air circulation to prevent vapor build up. Specifically, 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 to air, but once a breach has occurred it will likely remain a permanent problem, as a mechanism for correction will be difficult to implement. Thus, keeping in mind that the experiments described herein are conducted in a climate-controlled laboratory, comparison of the proposed insulation scheme with those commonly in use should minimize the biases. That is, thermo-physical properties to be calculated and contrasted are not skewed by manipulating the working conditions to optimize results.

CHAPTER III

EXPERIMENTAL APPARATUS

3.1 Experimental setup

The primary experimental apparatus used was part of L.I.C.H.E.N (LabVIEW Integrated Conduction Heat Experiment Network), composed of a vertical stack with three distinct segments, separated by two movable plates, as seen in Fig. 1. The middle stack housed the sample, 1in diameter maximum, to be tested with an upper and lower flux meter holding the sample in place. A Watlow 1500-watt band heater surrounded the source holder that held the upper flux meter in place. A Watlow 2000-watt power supply providing up to 200V at 10 amps supplied the band heater. The lower flux meter is attached to a heat sink cooled by an ethylene glycol/water solution supplied by a Forma Scientific 2161 constant temperature chiller. The column load was controlled mechanically and pneumatically with a bolted column combined with an air tank. Pressurization of the test specimen was achieved through use of load bellows, while an Interface 1110AF-1k low profile load cell tracked the history of the load. To ensure uniform load transfer, two stainless steel ball bearings are placed between the upper and lower movable plates.

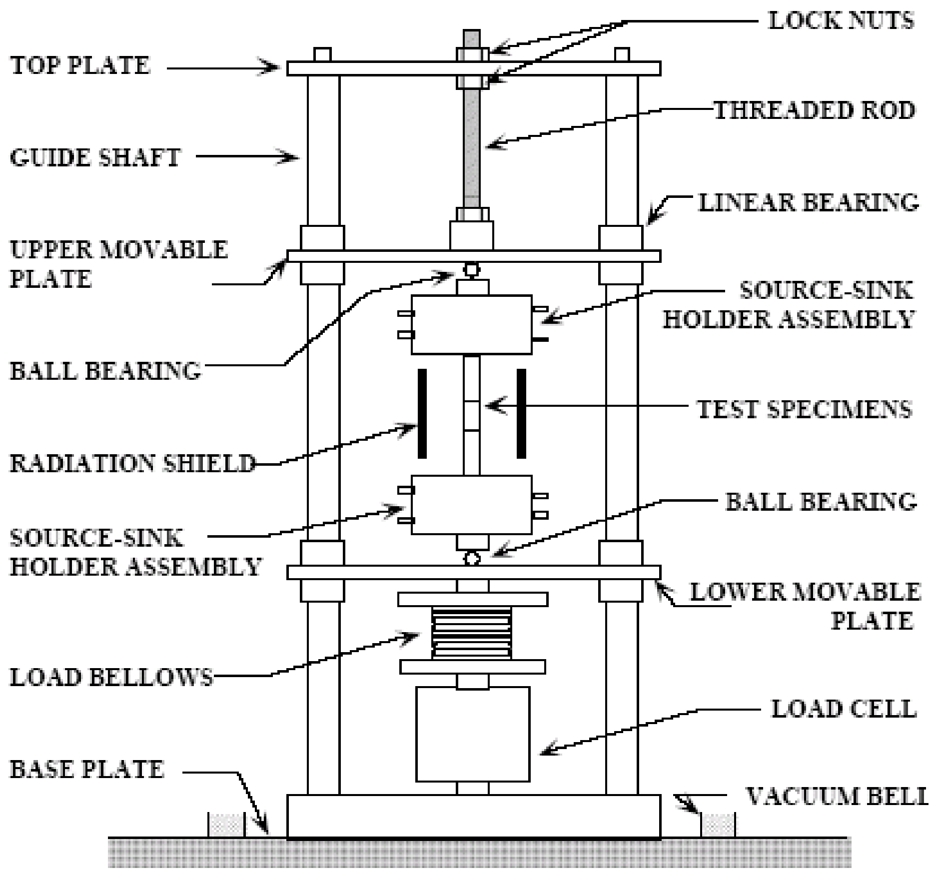

Fig. 1. Diagram of apparatus used in conducting the experiments

Flux meters were machined from small electrolytic iron cylinders (NIST reference material) into 1in. diameter by 2in. length samples with four small thermocouple holes drilled to centerline depth as seen in Fig.2. The thermocouple wells were fitted with 30-gauge SLE (special limit error) T-type thermocouples to centerline depth, aided by silver epoxy compound to ensure snug fit while minimizing thermal interference. Clear epoxy applied over the surface of the silver epoxy held the thermocouples in place.

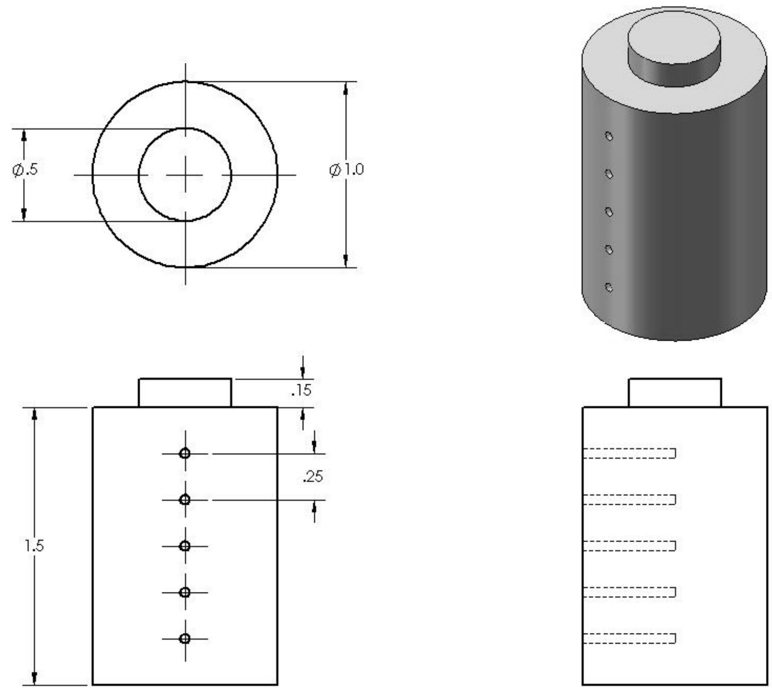

Fig. 2. Diagram of one of two identical flux meters used in experiments

Encasing the entire test column is an 18in. x 30in. Pyrex bell jar, Fig.3, which when used in conjunction with a vacuum pump, provides a testing environment free of convection. In most cases the vacuum pump was not employed to better simulate the working conditions of actual thermal insulations in service.

Fig. 3. Vacuum hood covering Pyrex bell jar

A hollow Teflon™ cylinder, Fig.4, machined to fit tightly around the flux meters, was used to house the wire mesh insulations of varying layers while securely enclosing the hollow glass microspheres.

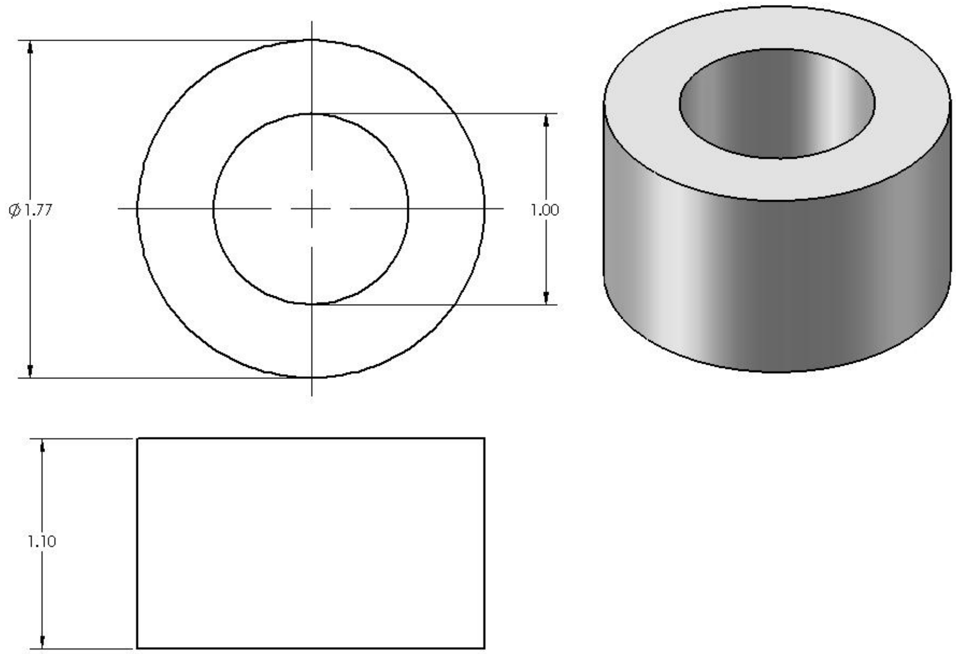

Fig. 4. Teflon™ cylinder used to hold test samples

3.2 Testing materials

The wire mesh used throughout the investigation was a 316 stainless steel 5-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 sea water. This is especially useful as the proposed insulation could be used in subsea pipes or other demanding environments. Several other metals also exhibit good resistance to degradation, but were not chosen due to economic considerations. Also, keep in mind this investigation is focused on the conceptual design of a multilayer wire mesh based insulation, rather than a materials selection exercise indicative of well established design concepts. Choice of readily available stainless steel wire mesh allows for its generous use in performing a number of test runs. The choice of 5-mesh size was based on experiments previously performed revealing it's optimum size in minimizing heat transfer in a controlled laboratory environment [12]. Here, the parameters of the tested wire mesh in juncture with the enclosure bears a Raleigh number far below the critical value for rectangular cavities [13]. Thus, resistance due to viscous forces cannot be overcome by buoyancy forces, meaning there is no advection within the cavity.

The glass microspheres used were supplied by 3M™ with three particular classifications S15, S35 and S60HS. The relevant thermal properties as provided by 3M™ are listed in Table 1. All three are of the same chemical composition of soda lime borosilicate glass with numeric codes representing the typical true densities of each with HS short 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 established.

Table 1
3M™ Glass Bubbles properties of interest

Product Code	**S15**	**S35**	**S60HS**
Typical True Density(g/cc)	0.15	0.35	0.6
Thermal Conductivity at 294K(W/m-K)	0.055	0.117	0.2
Crush Strength with 90% survival (psi)	300	3000	18000

Lastly, the selection of the liner used as a barrier between each layer of wire mesh, to function as a trap for filler materials, must be carefully considered. Here, there exist a wide variety of possibilities, depending on the properties demanded. Because the design of the proposed insulation is of primary focus, a liner was simply chosen to match the wire mesh in primary composition - namely iron based alloys. This compatibility is rather crucial, as a metallic wire mesh paired with a liner exhibiting vastly differing mechanical or thermal properties could lead to unforeseen incidents of degradation and failure. Also, the selection aims to confirm the validity of a metallic wire mesh-based insulation system, which could be made rather difficult in the case where the liner material has already been shown to perform as thermal insulation. With such considerations in mind, galvanized steel sheet was chosen throughout the investigation as a liner material because it was readily available and meets the outlined criteria. Galvanized steel is a widely used material well known for its workability, but not particularly for its thermal performance, so it should not impact the validity of possible findings.

A diagram of the overall setup for each sample tested, consisting of alternating layers of wire 5-mesh and liner, housed in the Teflon™ sample holder with eight layers is shown in Fig. 5. Addition of hollow glass microspheres would fill the voids in each wire mesh, with each liner separating microspheres between each layer.

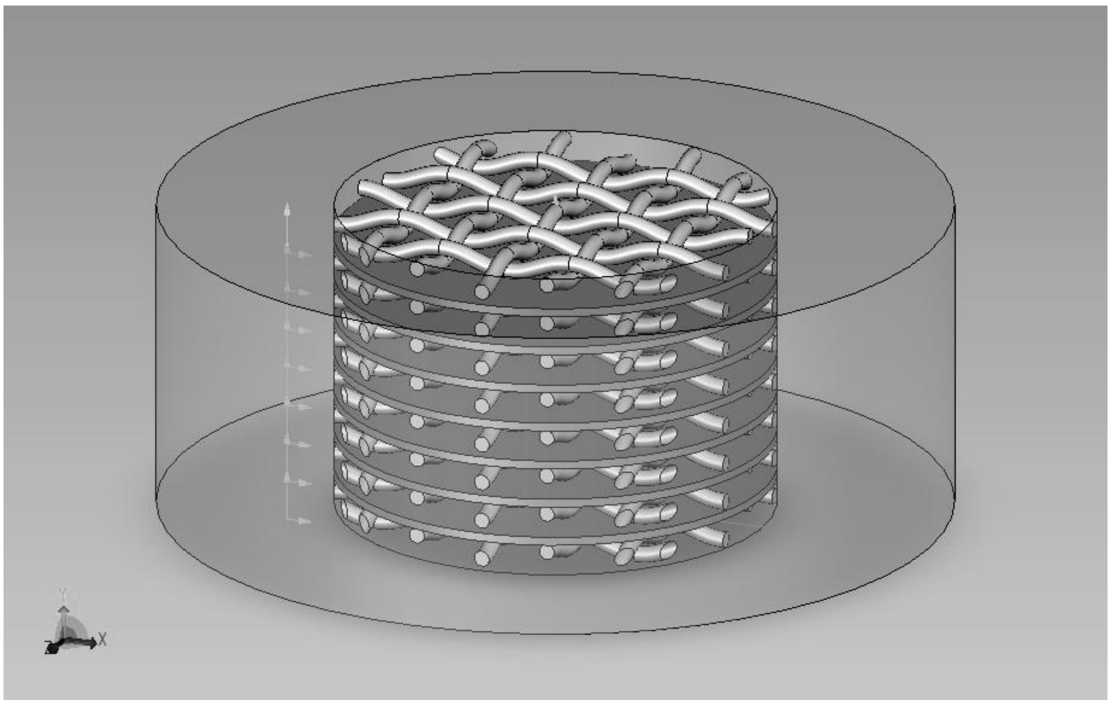

Fig. 5. Diagram of overall setup for each sample tested consisting of alternating layers of wire 5-mesh and liner housed in the Teflon™ sample holder (Eight layers shown)

CHAPTER IV

EXPERIMENTAL PROCEDURE

Three primary variables, including the number of wire mesh layers, the filler material, and temperature dependence, were investigated with the aim of being able to conclude whether or not a combination of metallic wire mesh and hollow glass microspheres represents insulation technology superior to those existing in the market. A set number of experiments were to be performed, once the parameters related to the three primary variables were chosen.

The primary experimental apparatus is part of L.I.C.H.E.N (LabVIEW Integrated Conduction Heat Experiment Network), a setup whose basic components allow three vertically stacked samples to be thermally and mechanically controlled. The upper and lower samples are of well-known standardized materials, with the middle being the material of interest. Knowing the temperature profile in the upper and lower samples allows for determination of thermal conductivity of the middle material through the use of Fourier's law.

The numbers of layers to be investigated are two (2), four (4), six (6), and eight (8), while filler materials included air, s15, s35 and s60HS hollow glass microspheres. All possible combinations will be exhausted with each run at four temperatures 300K, 330K, 366K and 400K. These temperatures represent the temperature at the upper interface between the upper flux meter and the test sample. All of which will be set for interface pressurization of 20 psi (1.36 atm) on the sample composite structure. The working environment will be air in all cases. In addition a few cases will also be run under vacuum in order to estimate heat losses.

In addition, validity of the experiments performed will be verified through use of a well-established model [8], which can be modified to represent the proposed insulation system, given certain assumptions. The degree of agreement should reinforce the validity of the findings and conclusions.

Table 2
Testing parameters

Consideration	Description
Wire Mesh	316 Stainless steel 5-mesh wire cloth plain weave (0.9mm Dia.)
Glass Microsphere	3M® Glass bubbles code: s15, s35, s60HS
Sheet Liner	Galvanized steel 24GA. (0.5mm thick)
Test Sleeve	Machined Teflon™ cylinder (inner dia. 1in)
Upper Interface Temperature(K)	300, 330, 366, 400
Loading Pressure	20 psi
Environment	Ambient, medium vacuum

CHAPTER V

DATA REDUCTION AND UNCERTAINTY ANALYSIS

Estimating the thermal conductivity for this particular setup was relatively straightforward, involving the use of Fourier's Law. The parameters required for the necessary calculations included heat flux, q''; temperature drop across the insulation, ΔT and thickness of the insulation, t. To obtain the heat flux, the steady-state temperature readings of the flux meters were used to find the temperature gradients across the meters via linear regression, and applying Fourier's Law with known conductivity of the flux meter. In order to ensure minimal bias the average of the upper and lower heat fluxes was taken as the final heat flux used to estimate effective conductivity of the insulations.

Since electrolytic iron is a standard NIST material, thermal conductivity values are readily available as a function of temperature.

$$q''_{upper} = -k_{fluxmeter} \frac{dT}{dx}_{upper} \tag{5.1}$$

$$q''_{lower} = -k_{fluxmeter} \frac{dT}{dx}_{lower} \tag{5.2}$$

$$q'' = \frac{1}{2}\left(q''_{upper} + q''_{lower}\right) \tag{5.3}$$

To find the temperature drop across the testing specimen, the linear regressions, based on four thermocouple points each, for the upper and lower temperature profiles of the flux meters, were extrapolated to their respective interface positions with the difference between them being ΔT. The extrapolated temperatures at the upper and lower interfaces are denoted by T_u^* and T_l^*, respectively with $\Delta T = T_u^* - T_l^*$. Note that the slopes of the upper and lower linear regression seen in Fig. 5.1, denoted m_u and m_l represent the temperature gradient of those respective flux meters. Here an assumption was made to neglect contact resistance at both upper and lower interfaces due to their relatively small contributions as compared to the resistance of the test sample. Finally, thickness of each test sample, measured both before and after testing to ensure uniformity, was easily obtained via digital calipers.

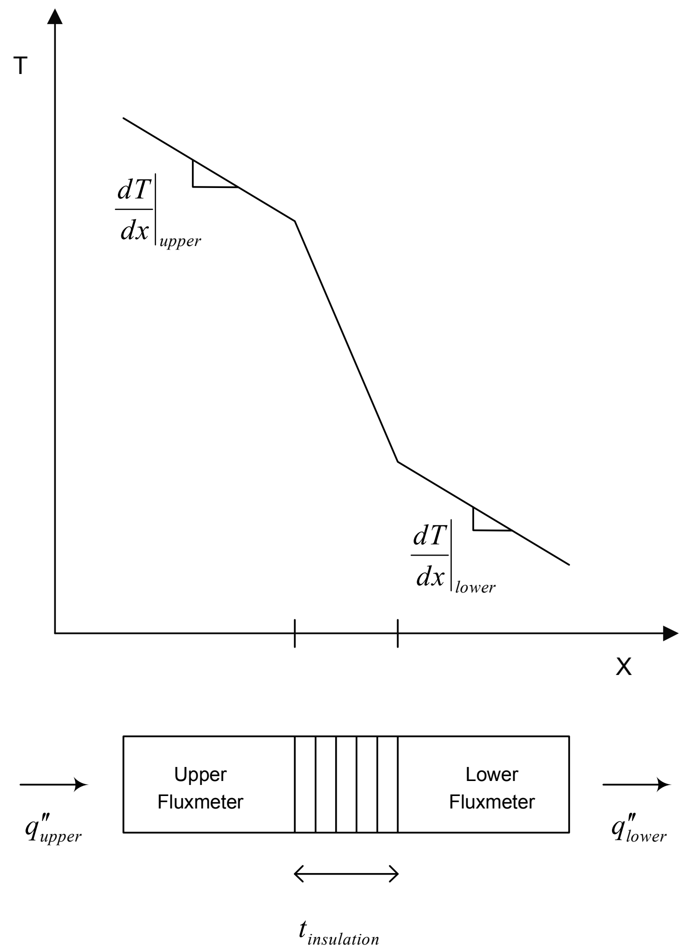

Fig. 6. Diagram of sample temperature profile through the test stack

Upon obtaining the three required parameters, effective thermal conductivity of the insulation can be calculated. Refer to appendix A for sample calculations.

$$k_{effective} = \frac{q'' t_{insulation}}{\Delta T} \tag{5.4}$$

The Kline-McClintock method [23] was used to estimate the uncertainty associated with the thermal conductivity estimation. If R is a function of independent variables x_1, x_2, x_3,..., x_n then the uncertainty associated with R may be expressed in terms of those independent variables and their respective uncertainties.

$$R = f\left(x_1, x_2, x_3, ..., x_n\right) \tag{5.5}$$

$$w_R = \left[\left(\frac{\partial R}{\partial x_1} w_{x_1}\right)^2 + \left(\frac{\partial R}{\partial x_2} w_{x_2}\right)^2 + ... + \left(\frac{\partial R}{\partial x_n} w_{x_n}\right)^2\right]^{\frac{1}{2}} \tag{5.6}$$

Upon completing the appropriate calculations, the uncertainty of the effective thermal conductivity can be deduced. However, it is often more appropriate to obtain the relative uncertainty in order to understand the significance of the uncertainty involved.

By simply dividing the uncertainty by the calculated value, relative uncertainty is obtained. The mathematical derivations appear in appendix B, with the result of interest shown in (5.7).

$$\frac{w_{k_{effective}}}{k_{effective}} = \left[\frac{(m_u^2 + m_l^2)w_k^2 + (k_{upper} w_{m_u})^2 + (k_{lower} w_{m_l})^2}{(k_{upper} w_{m_u} + k_{lower} w_{m_l})^2} + \frac{w_{T_u^*}^2 + w_{T_l^*}^2}{(T_u^* - T_l^*)^2} + \left(\frac{w_{t_{insulation}}}{t_{insulation}}\right)^2\right]^{\frac{1}{2}} \tag{5.7}$$

Here the full uncertainty equation involves values that have yet to be discussed, but more importantly all variables can be calculated or measured with minor effort. The uncertainty involved in the linear regression-based values was obtained using a simple statistics algorithm via Microsoft Excel®, assuming a ninety percent confidence interval. The relative uncertainty assumed in the thermal conductivity of the electrolytic iron flux meters was five percent, representing a worst case, as values are well established with NIST.

Overall the uncertainties associated with effective thermal conductivity ranged from ten to twenty percent of the calculated value in all but a few runs of experiments. This represents a relatively solid foundation for the analysis phase for the findings in the investigation. It should be mentioned that uncertainties below ten percent would have provided more confidence for the findings gathered. However, this lower uncertainty was not possible working within the framework of the laboratories capabilities.

CHAPTER VI

PRESENTATION AND DISCUSSION OF RESULTS

6.1 The effective thermal conductivity of multiple wire mesh layers with air as filler

The computed effective thermal conductivity for multiple layers of wire mesh insulation, with air as the filler material, as a function of mean interface temperature, is shown in Fig. 7. Increasing the number of wire mesh layers from two to eight results in an increase in the corresponding effective thermal conductivities, although each successive increase becomes less pronounced with more layers. This is quite clear as six and eight layers of wire mesh yield values that are not statistically different. The observed result tends to be counter-intuitive, as an increase in the number of layers should result in more resistance to heat flow, and thus a lower thermal conductivity (which indicates a material's ability to transfer heat). Closer examination, specifically the experimental setup, reveals some insights as to a possible explanation for the counter-intuitive results. The drop in temperature for all layers at each specified upper interface temperature remained relatively constant, indicating that the average heat flux across the insulation played a key role in determining the 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, as a function of upper interface temperature, is shown in Fig. 8. This result does not defy conventional wisdom, as was implied by only observing the effective thermal conductivity independently.

A closer look into the physical make-up of each layer provides significant insight into the heat transfer mechanisms involved. The number of layers was determined only with regard to the wire mesh; the number of liner layers used was always one less than the number of wire mesh layers. When viewed in terms of the ratio of wire mesh layers to liner layers, the investigated insulation setups did not consistently match. For instance, 2 layers of wire mesh yielded a wire mesh to liner ratio of 2:1, 4 layers, 4:3, 6 layers, 6:5, and 8 layers, 8:7. Thus, the 2 layer cases represented an insulation setup far different from the others. As seen in fig. 7, the 2 layer cases had effective thermal conductivities significantly lower than the other cases. Meanwhile, there exist overlaps in the thermal conductivities of the four, six and eight layer cases.

In terms of heat transfer mechanisms, in the 2 layer cases, interaction between the liners did not exist due to there being only a single layer of liner material. With added layers, this is no longer the case, and multiple liner layers may have acted as "heat capacitors" and "heat spreaders". The relatively poor insulating liner material used most likely allowed for relatively free flow of heat from liner-to-liner until the temperatures between layers normalized. Effectively, leaving a single layer at the endpoints where liner-to-liner interaction was no longer present. As indicated by the higher effective thermal conductivities relative to the two layer cases, liner-to-liner interaction with more layers acted to promote heat transfer, rendering the overall insulation less effective.

In examining the role interface temperature plays in effective thermal conductivity, it is not apparent that any link exists, given the uncertainties involved. Also, at the maximum temperature studied of 400K, the stainless steel wire mesh and galvanized steel sheet are at the lower end of their capable operating conditions, and significant changes in their respective thermal conductivities are not expected.

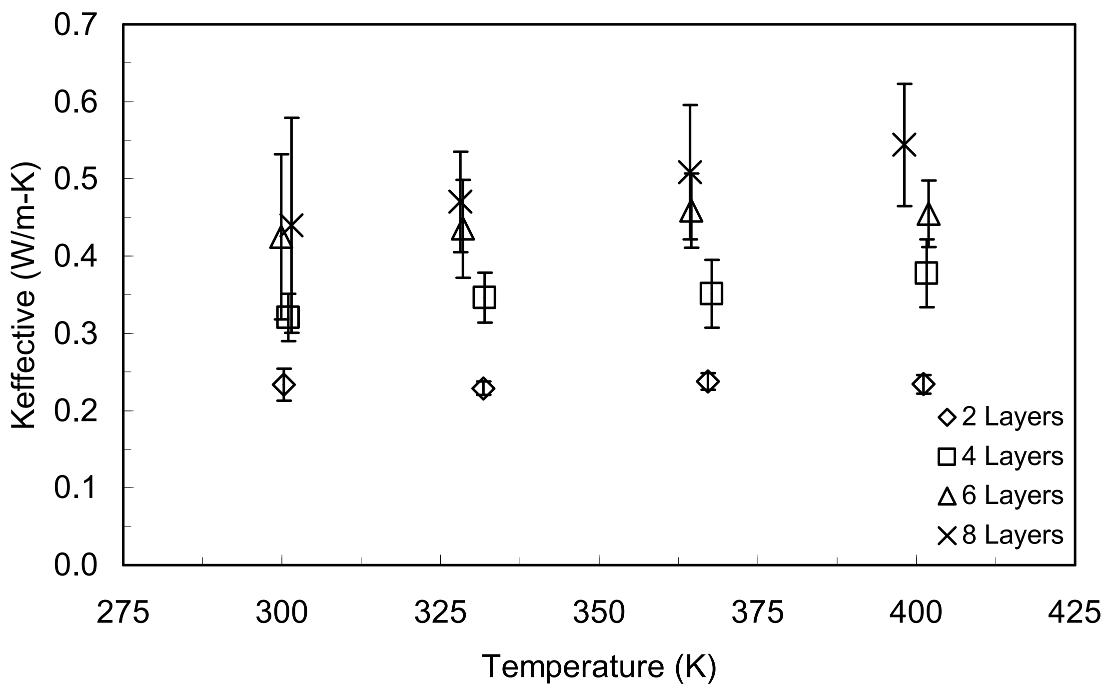

Fig. 7. Effective thermal conductivity of multiple wire mesh layers as a function of upper interface temperature

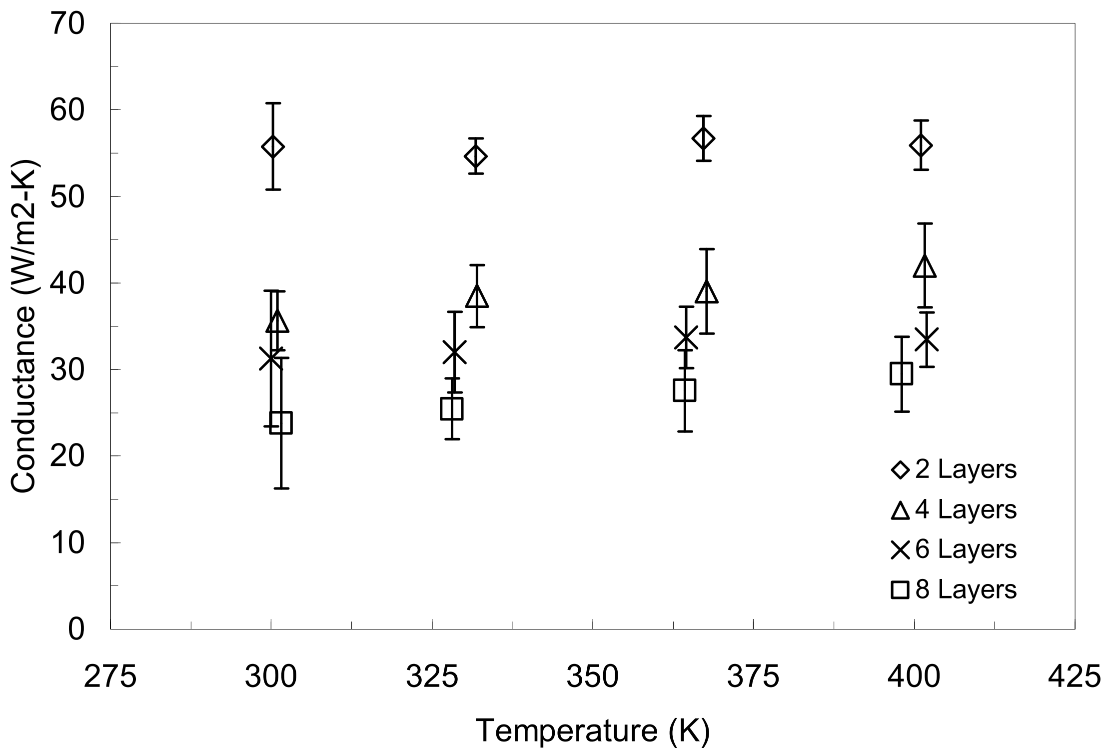

Fig. 8. Thermal conductance of multiple wire mesh layers as a function of upper interface temperature

6.2 The effective thermal conductivity of multiple wire mesh layers with s15 hollow glass microspheres as filler

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 upper interface temperature, is shown in Fig. 9. Introducing s15 hollow glass microspheres, the effective thermal conductivity of multiple layers indicates insignificant changes in the trends observed when compared with Fig. 7. That is, the addition of s15 hollow glass microsphere did not introduce unforeseen changes in effective thermal conductivity to 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 cases of four, six and eight layers. Also, there seems to be a slight upswing in effective thermal conductivity with increasing temperature, but given the computed uncertainties, the correlation is weak.

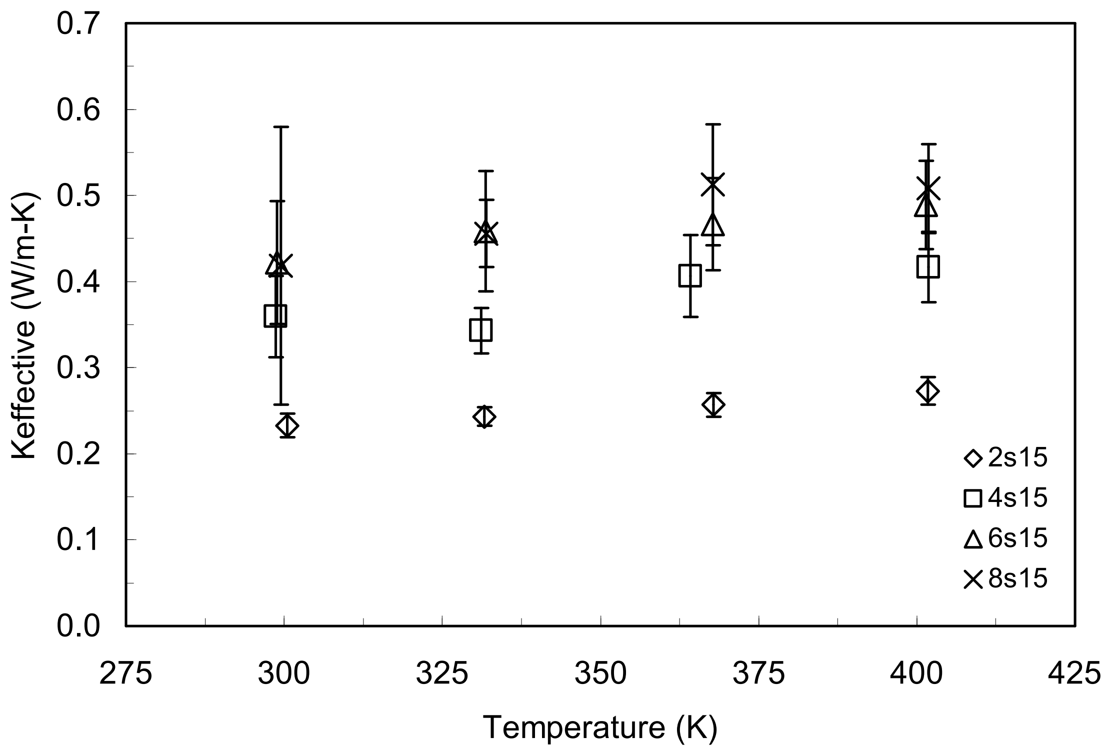

Fig. 9. Effective thermal conductivity of multiple wire mesh layers with s15 hollow glass microsphere as filler material as a function of upper interface temperature

6.3 The effective thermal conductivity of multiple wire mesh layers with s35 hollow glass microspheres as filler

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 upper interface temperature, is shown in Fig. 10. Looking at s35 hollow glass microspheres, the calculated effective thermal conductivity hardly differs as compared with prior cases, with only a slight nuance that can be explored. 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. 9, 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 ~2 times that for s15), there is a larger impact as the number of layers increases. Given that effective thermal conductivity already increases with additional layers, the addition of hollow glass microsphere filler appears to disproportionately affect the higher number of layers cases, further reducing its effectiveness as a thermal barrier.

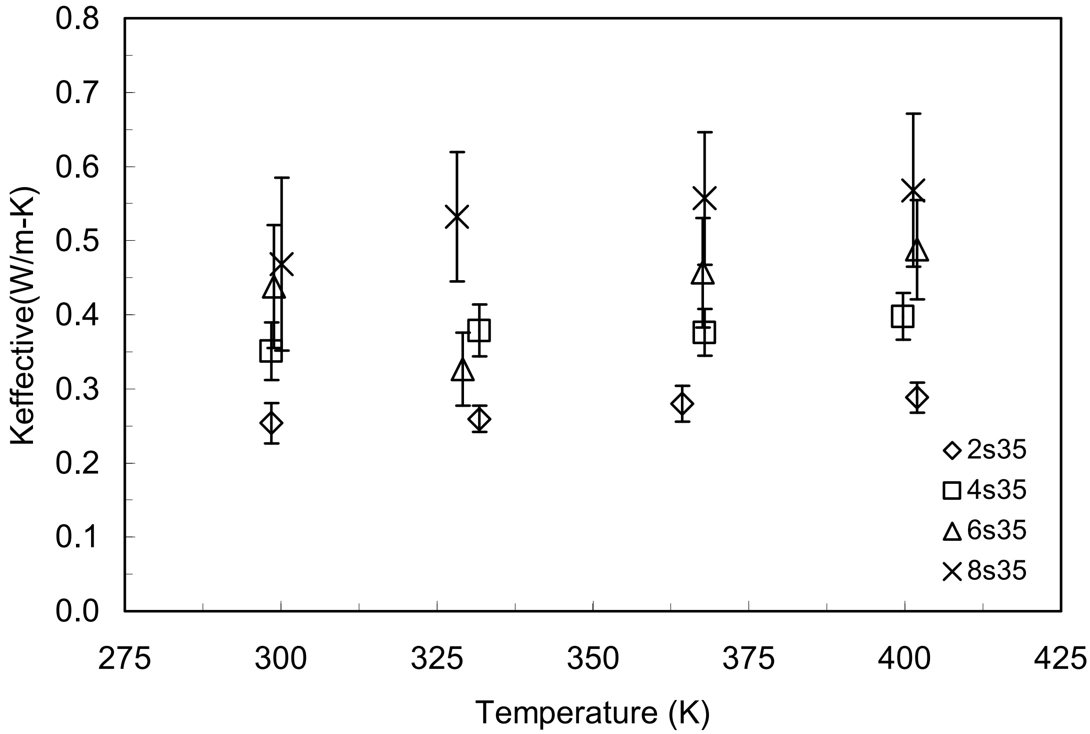

Fig. 10. Effective thermal conductivity of multiple wire mesh layers with s35 hollow glass microsphere as filler material as a function of upper interface temperature

6.4 The effective thermal conductivity of multiple wire mesh layers with s60HS hollow glass microspheres as filler

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 upper interface temperature, is shown in Fig. 11. Here the separation of effective thermal conductivity values between each layer, as shown in Fig. 11, is even more defined than in previous cases. This confirms the previous hypothesis of disproportionate increases in effective thermal conductivity values in cases of higher numbers of layers with hollow glass microspheres added.

The thermal conductivity of s60HS hollow glass microspheres independently is 0.2 W/m-K, 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 will tend to accentuate previous trends found with s15 and s35 microspheres. Given this development, something must be said as to why fillers disproportionately influence the effective thermal conductivity as more layers are introduced. As observed, increasing the number of layers means increasing the volume of hollow glass microspheres present, and when viewed in terms of thermal resistance, this does explain the phenomena. The increased volume means increased surface area for heat transfer, thereby effectively reducing thermal resistance, a damaging outcome for all types of thermal insulation.

Recall from section 6.1 that additional layers provided greater thermal resistance. Thus, the addition of a larger volume of a filler material with thermal conductivity higher then that of air acts to reduce the overall thermal resistance. For instance, in the two layer cases where thermal resistance was already relatively low, 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 a large increase in conduction paths with the results clearly seen by significant increases in effective thermal conductivities. In light of this development, it can be preliminarily inferred that the addition of hollow glass microspheres does not improve thermal resistance performance as measured by the effective thermal conductivity of wire screens. Further examination into the effects of various sizes of hollow glass microsphere on each particular number of layers should corroborate this finding.

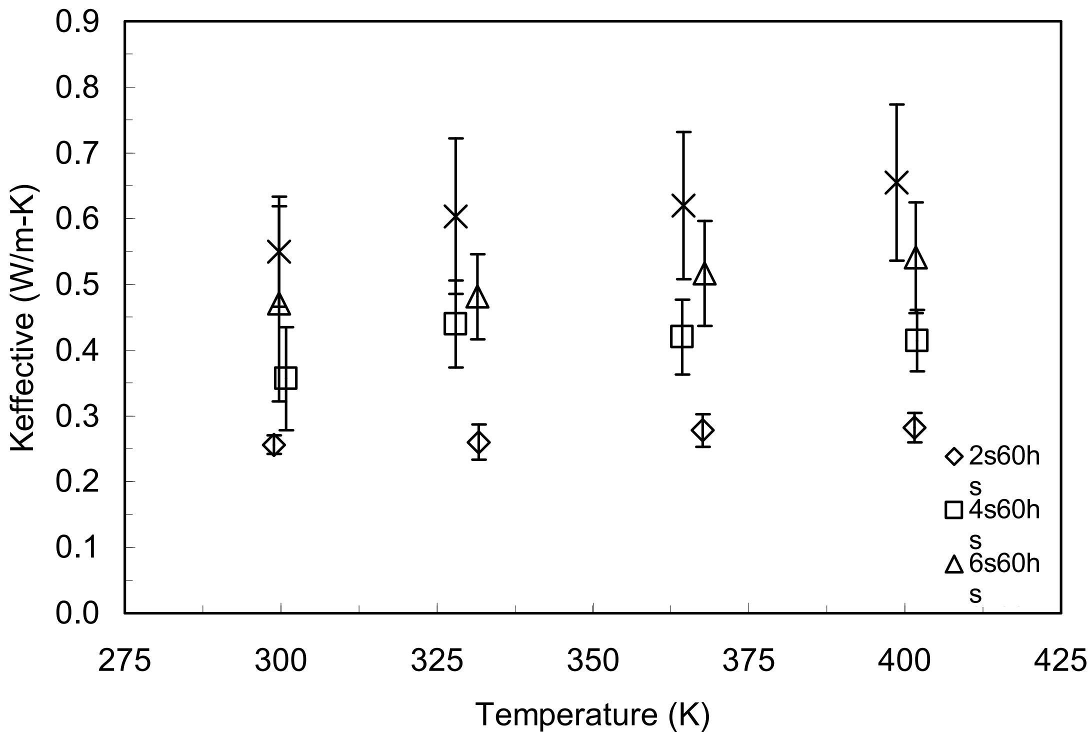

Fig. 11. Effective thermal conductivity of multiple wire mesh layers with s60HS hollow glass microsphere as filler material as a function of upper interface temperature

6.5 The effective thermal conductivity of two wire mesh layers with air and s15, s35 and s60HS hollow glass microspheres as filler materials

The following four sections aim to further discuss the possible use of multiple metallic wire mesh layers with hollow glass microspheres as a conduction barrier. Keep in mind from Fig. 7 that two wire mesh layers with air as filler yielded the lowest effective thermal conductivity values of approximately 0.23-0.24 W/m-K, depending on tested temperature. The effective thermal conductivity of two wire mesh layers as a function of upper interface temperature with air and s15, s35, s60HS hollow glass microspheres as filler materials is shown in Fig.12.

The results found in Fig. 12, although not absolutely conclusive (due to 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, the densest of all the filler materials, where there is a statistically significant increase in effective thermal conductivity as compared to 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.

It was hypothesized that addition of a filler material such as glass microspheres would limit the conduction of air within the wire mesh, yielding more resistance to heat flow. More specifically, with hollow glass microspheres the “mean free path” for air conduction would be reduced significantly as compared with the unfilled air cavity. However, by introducing filler material, there is the possibility that heat transfer by conduction and radiation via the filler material may negate the reduced bulk air conduction effect. This is hardly surprising as thermal conductivity values for all three types of glass microspheres tested were higher than that of air, and 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 filler cases where effective thermal conductivity remained relatively constant with increasing temperature. This behavior is most likely due to the temperature dependence of thermal conductivity of the hollow glass microspheres. More significant is the general increase of heat transferred through radiation, which is the dominant mode of heat transfer for microspheres above room temperature [14]. In contrast, for the wire mesh, although subject to thermal conductivity changes and radiation effects, having a significantly smaller surface area resulted in negligible changes in effective thermal conductivity values.

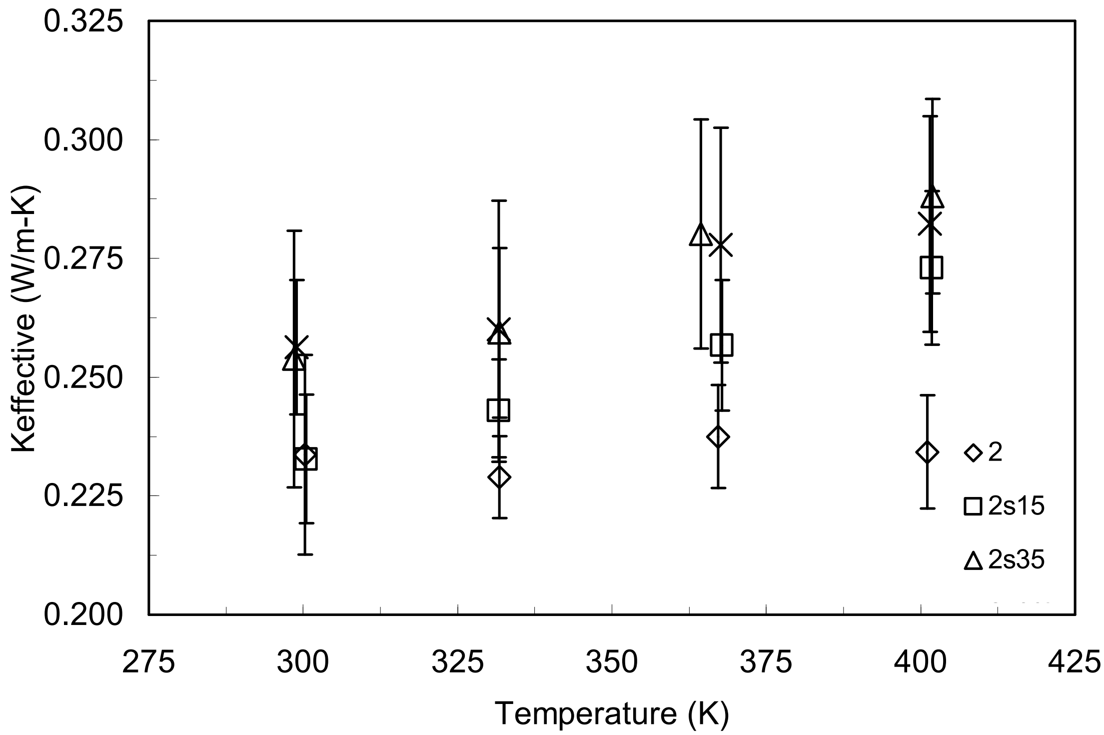

Fig. 12. Effective thermal conductivity of two wire mesh layers as a function of upper interface temperature with air and s15, s35, s60HS glass microspheres as filler materials

6.6 The effective thermal conductivity of four wire mesh layers with air and s15, s35 and s60HS hollow glass microspheres as filler materials

The effective thermal conductivity of four wire mesh layers, as a function of upper interface temperature, with air and s15, s35, s60HS hollow glass microspheres as filler materials, is shown in Fig.13. 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 addition of glass spheres does not result in significantly measurable changes in effective thermal conductivity values.

With some caution it can be said that the number of layers used largely determines the overall effective thermal conductivity values, with filler materials having secondary minor effects. This hypothesis should be readily verifiable as the trends in the six and eight layer cases are revealed. This would suggest that once the number of layers in the insulation design is selected there is very little that can be done to change the overall behavior of the insulation system. Note also there appears to be a slight dependence on temperature, as 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.

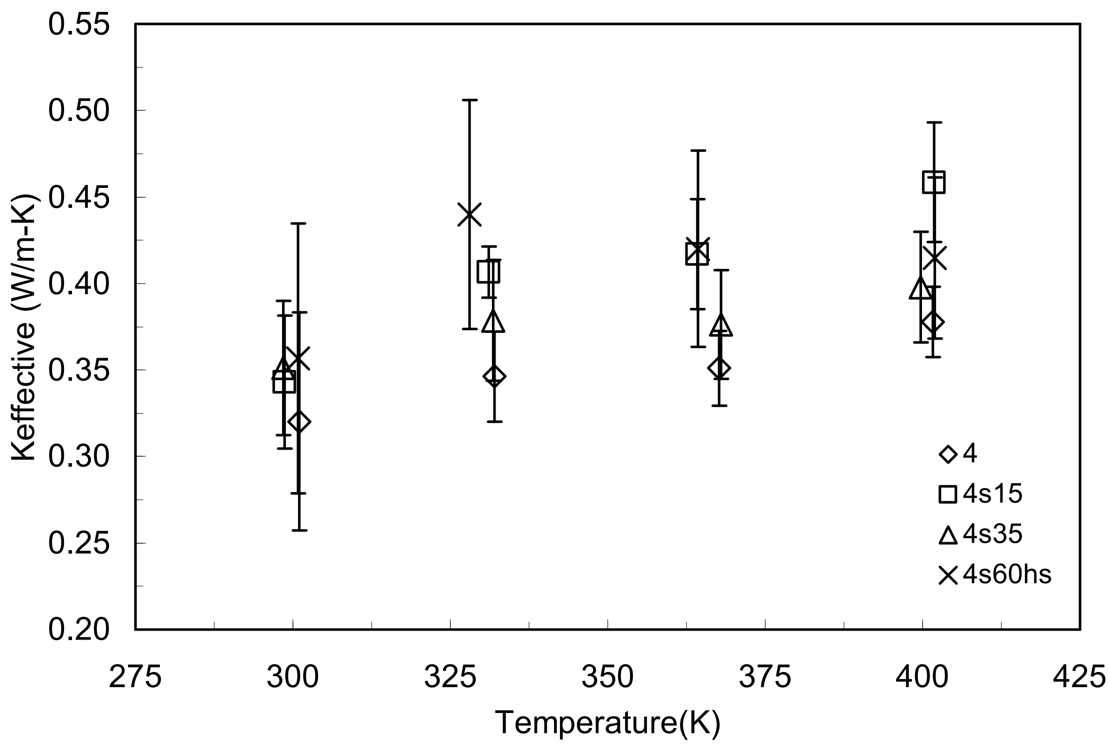

Fig. 13. Effective thermal conductivity of four wire mesh layers as a function of upper interface temperature with air and s15, s35, s60HS glass spheres as filler materials

6.7 The effective thermal conductivity of six wire mesh layers with air and s15, s35 and s60HS hollow glass microspheres as filler materials

The effective thermal conductivity of six wire mesh layers, as a function of upper interface temperature, with air and s15, s35, s60HS hollow glass microspheres as filler materials, is shown in Fig.14. Here again the overlap in the effective thermal conductivity values, as shown in Fig. 14, reveals very little in terms of differentiating the cases. The most that can be said 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 introduced hypothesis that the number of layers plays a far more critical role in determining the effective thermal conductivity, with filler material having a minor effect.

Even less can be said about temperature dependence, since a link is not visibly present. Also, there appears to be an outlier in the effective thermal conductivity value of the s35 glass sphere case at around 330K, where the effective thermal conductivity is significantly lower than the presently visible trend would suggest. Certainly there are many possibilities that may lead to such an appearance, but if no logical reason based on previously observed evidence can be found to explain such behavior, it must be considered an experimental outlier. For at 330K the properties of the tested materials do not exhibit an extremum, and great care was taken to follow a strict protocol in setting up each test run. Thus, the peculiar result can only be said to deviate from previously observed trends and experimental norms. Further experimentation is required to either verify or disprove the existence of the outlier.

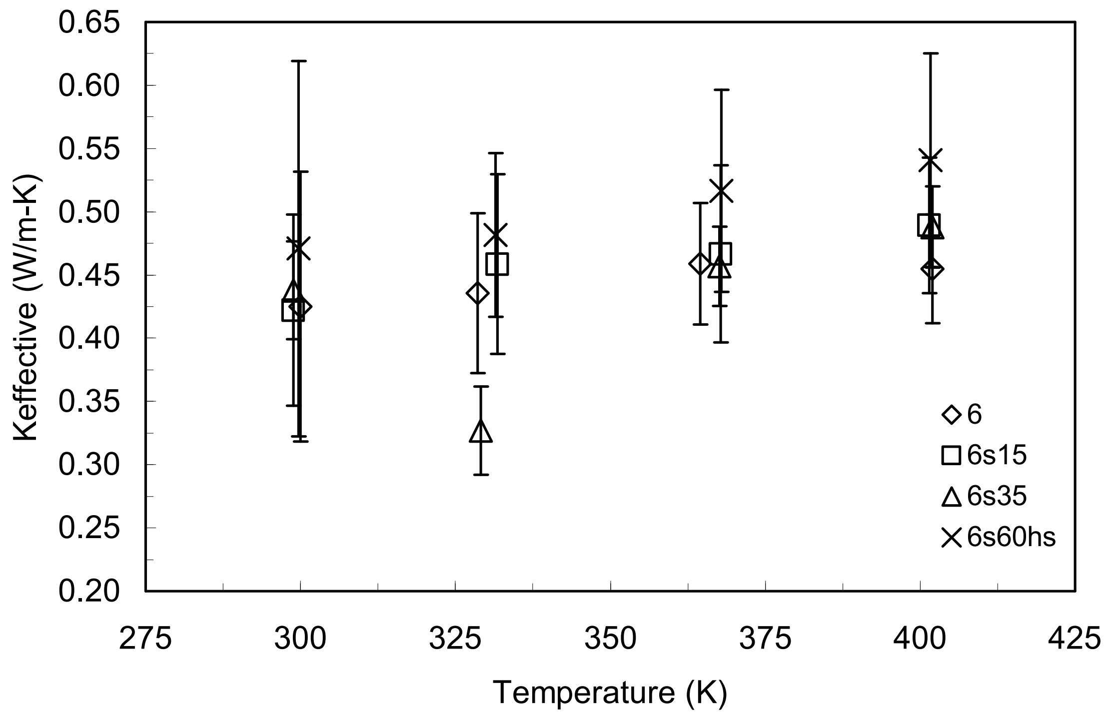

Fig. 14. Effective thermal conductivity of six wire mesh layers as a function of upper interface temperature with air and s15, s35, s60HS glass spheres as filler materials

6.8 The effective thermal conductivity of eight wire mesh layers with air and s15, s35 and s60HS hollow glass microspheres as filler materials

The effective thermal conductivity of eight wire mesh layers, as a function of upper interface temperature, with air and s15, s35, s60HS hollow glass microspheres as filler materials, is shown in Fig.15. Not unexpectedly, with eight layers the estimated effective thermal conductivity, shown in Fig. 15, follows similar trends found in the four and six layer cases as seen in Figs. 13,14. As with the four and six layer cases, the effective thermal conductivity values of eight wire mesh layers having various filler materials do not separate themselves sufficiently to infer statistically significant variations between them. This again confirms the importance of the number of mesh layers over filler materials on the overall effective thermal conductivity values. 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.

To summarize, the use of glass microspheres as filler material for the tested wire mesh structures appears to have negligible impact on the effective thermal conductivity of the insulation, given the uncertainties inherent throughout the experiments. Even with the assumption that all calculated values represent actual values, meaning no uncertainty is involved, addition of hollow glass microspheres in all instances increases the effective thermal conductivity value by approximately 5% to 25% as compared to air as a filler material. This development can be traced to the initial attempt to reduce bulk conduction of air within the voids of the wire mesh. Given the results described in this and previous sections, it can be confidently inferred that air gap conduction was relatively limited to begin with, and thus attempts at further reduction can only come at the expense of increased heat transfer via hollow glass microsphere conduction and radiation. 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 transformed the air void filled wire mesh structure into a wire mesh and hollow glass microsphere hybrid with significantly increased surface area for heat transfer. With observably less resistance, due to much lower void volume, it is no surprise that increases in effective thermal conductivity were observed in many cases. This effect is most apparent with s60HS hollow glass microsphere, having thermal conductivity approximately 8 times higher than air, where 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 run.

These results have the added effect of indirectly reaffirming the choice in size and configuration of wire mesh which optimizes a high thermal conductivity wire material, with air gaps between wires, in terms of producing limited natural convection (no advection) and limiting air conduction within the voids. Thus it appears that any attempt to introduce a filler material with thermal conductivity higher than air to the tested wire mesh can only adversely impact the effective thermal conductivity by increasing it. However, there is the possibility that given certain mesh sizes in which natural convection appears and dominates to a very high degree, the addition of materials such as glass microspheres may result in a reduction in effective thermal conductivity. Such speculation is beyond the scope of this particular study.

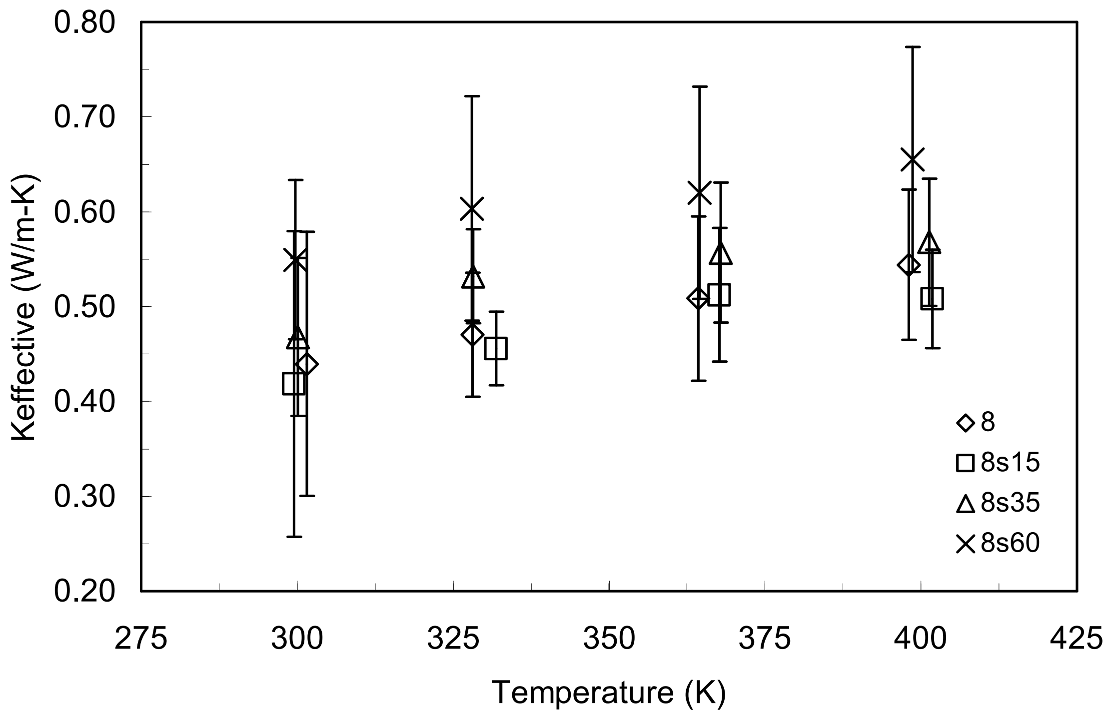

Fig. 15. Effective thermal conductivity of eight wire mesh layers as a function of upper interface temperature with air and s15, s35, s60HS glass spheres as filler materials

6.9 The effective thermal conductivity of multiple SS 316 wire mesh layers under medium vacuum

Several experiments were performed without a filler material, under vacuum conditions, with pressures ranging from 9 – 27 Pa, with the intent of determining heat losses due to radiation within the test chamber. However, unforeseen difficulties arose with the functioning of the test apparatus whereby results did not fully converge or uncertainties surpassed an acceptable limit. Thus the results that were recovered cannot be shown against those from previous ambient runs because a comparison would be largely incomplete.

Certainly something must be said regarding the heat losses involved, as they may influence the results shown in prior sections. There are a couple of scenarios that warrant discussion. First, there is the possibility that the experimental setup with the Teflon™ sleeve in combination with a radiation shield had heat losses that were relatively low to begin with. Thus drawing a vacuum would have little or 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 flow paths, rendering results unchanged even with vacuum. Lastly, there is the unlikely prospect that heat losses were significant because the first two scenarios represent inaccurate portrayals of the actual conditions.

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 relatively limited as behavior under vacuum did not deviate from the non-vacuum counterpart.

6.10 Comparison of the effective thermal conductivity of multiple SS 316 wire mesh layers with D.K. Kim's model [13]

Prior to comparing the experimental results with those predicted by some analytical models, a general background detailing the model's intended use and possible limitations must be known. It would serve little purpose to contrast a model with experimental results under circumstances beyond the scope of the model. Here, the analytical models were designed to predict the thermo-physical properties of a single layer of screen mesh, as seen in Fig. 16. The inner and outer surfaces were assumed to each be at a specific constant temperature and thus a simple thermal circuit was built to simulate the thermal resistances through the screen mesh.

The analytical investigation yielded three distinct models: (1) macro (based on bulk deformation), (2)elastic micro contact, and (3) plastic micro contact, with the latter two taking into account surface asperities. The combined experimental and analytical investigation indicates that the plastic micro contact model was most accurate in predicting actual behavior with RMS error ranging from 10 – 19 %. The macro model, based on Hertzian contact theory, does not include micro contact effects, and was found to be the worst performer due to the assumption of perfect contact in the deformed area.

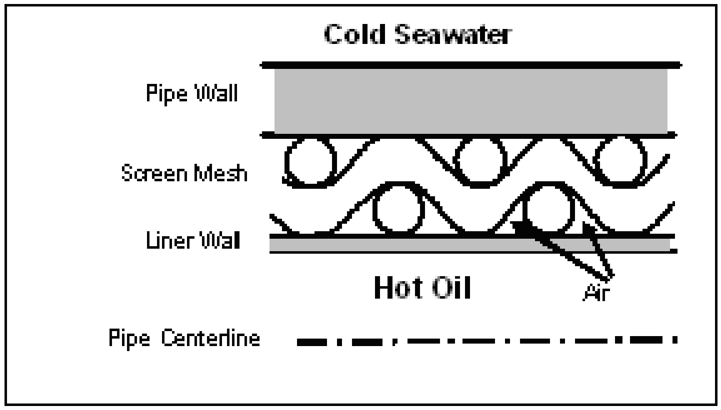

Fig. 16. Diagram of metallic wire mesh used as pipe insulation representing the motivation with which D.K. Kim's analytical models were developed

To adapt the single layer model for use in predicting thermo-physical properties in multiple layer cases certain assumptions were made. First, the input values for each material's properties must be uniform and constant, meaning for instance that thermal conductivities of the wire mesh through the various layers could not be a function of temperature. Given well defined temperature drops across each layer, in actuality thermal conductivity cannot be constant. Thus, care must be taken in the selection of the input variables to best correspond to each experimental test to be compared against. In particular, the experiments that were conducted did not include wide ranges of temperature. Because thermal conductivity of stainless steel 316 varies only approximately 10% between 300 and 400K, this is likely a small contributor to possible error values observed in the resulting prediction.

There exists a far bigger issue when dealing with the role of the liner separating each wire mesh layer. In extending the single layer models for predicting multiple layer cases, certain crucial aspects of the models break down, limiting their effectiveness in predicting thermo-physical properties in the proposed multilayer wire mesh insulation scheme. The basic thermal circuit used to represent the single layer wire mesh, while theoretically sound, cannot be extended to multiple layers without some modifications to include the thermal resistance contribution and thermal spreading effects due to the liner. Without the necessary adjustments, the extended models will tend to downplay the role of the liner.

The effective thermal conductivity of multiple wire mesh layers and predicted values using a Hertzian macro contact model, as a function of upper interface temperature, is shown in Fig. 17. Consider the macro model, based on Hertzian assumptions of frictionless and elliptical contacts, where given the relatively low interface pressure (~20 psi) used in the experiments should provide a decent initial estimate because inelastic contributions remain very low. As seen in Fig. 17, the macro model predicting effective thermal conductivity for multiple wire mesh layers reveals very little separation when subsequent layers are added, while being unaffected by temperature increases. The lack of separation is inconsistent with experimentally observed results, while predicted values were significantly lower in some cases. The only consistent aspect of the model seems to be the prediction of the independence of effective thermal conductivity with respect to the upper interface temperature. Here, the inability of the macro model to match clearly observable trends can be primarily attributed to the thermal spreading caused by the liner, which is neglected in the model. An increase in the number of layers appears to effectively increase the area in which heat is transferred through the liner, and thus thermal spreading becomes a larger contributor.

This is apparent as the agreement between experimental results and predicted behavior noticeably suffers as the number of layers progressively increases from two to eight.

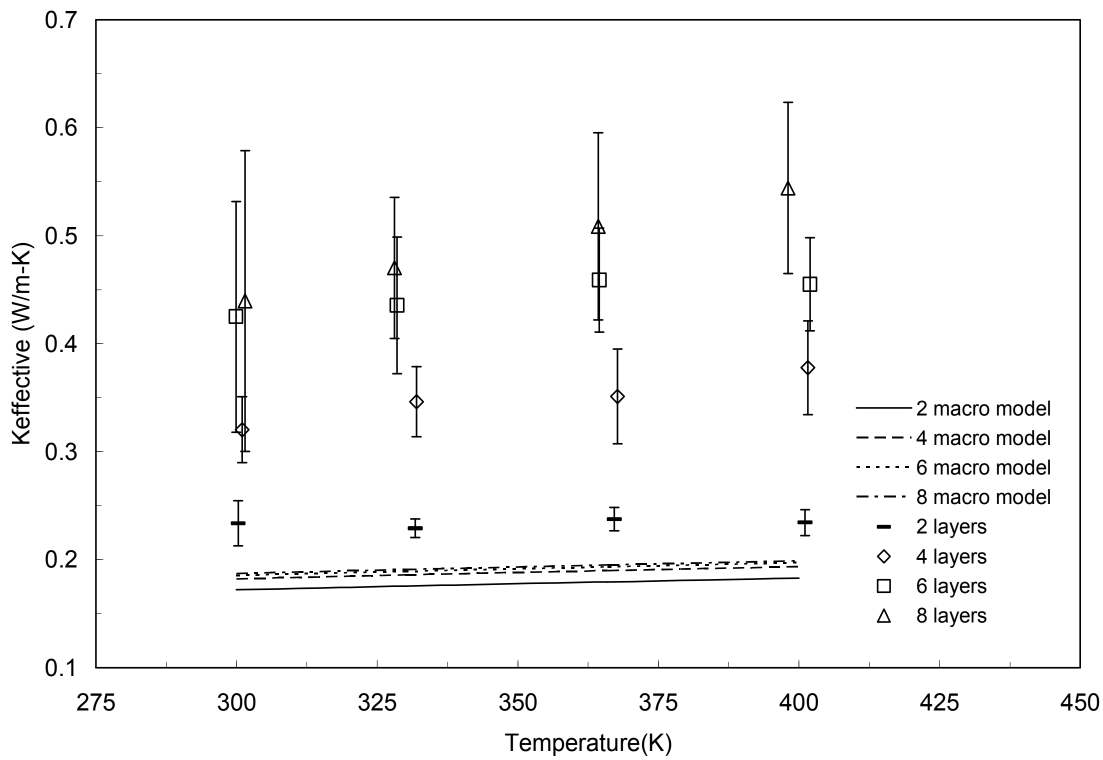

Fig. 17. Effective thermal conductivity of multiple wire mesh layers and predicted values using Hertzian macro contact model as a function of upper interface temperature

The effective thermal conductivity of multiple wire mesh layers and predicted values using a plastic micro contact model, as a function of upper interface temperature, is shown in Fig. 18. Consider the best performing model, plastic micro contact, where the assumption of perfect contact area is removed by taking into account the asperities associated with all real surfaces. Here again, in Fig. 18, as with the macro model, the plastic micro model appears to be under-predicting effective thermal conductivity values while failing to exhibit the significant trends with regard to layer separation.

It should be noted that the relatively low interfacial pressures (~20Psi) used in the experiments represent the lower extreme end at which the developed models were intended. By further considering inelastic micro contact conditions, the predicted values become further removed from observed values by reducing the area for pure conduction with the presence of asperities. This is in addition to suffering from the same limitations as the macro model in neglecting thermal spreading in the liner, and yields less than desirable prediction power.

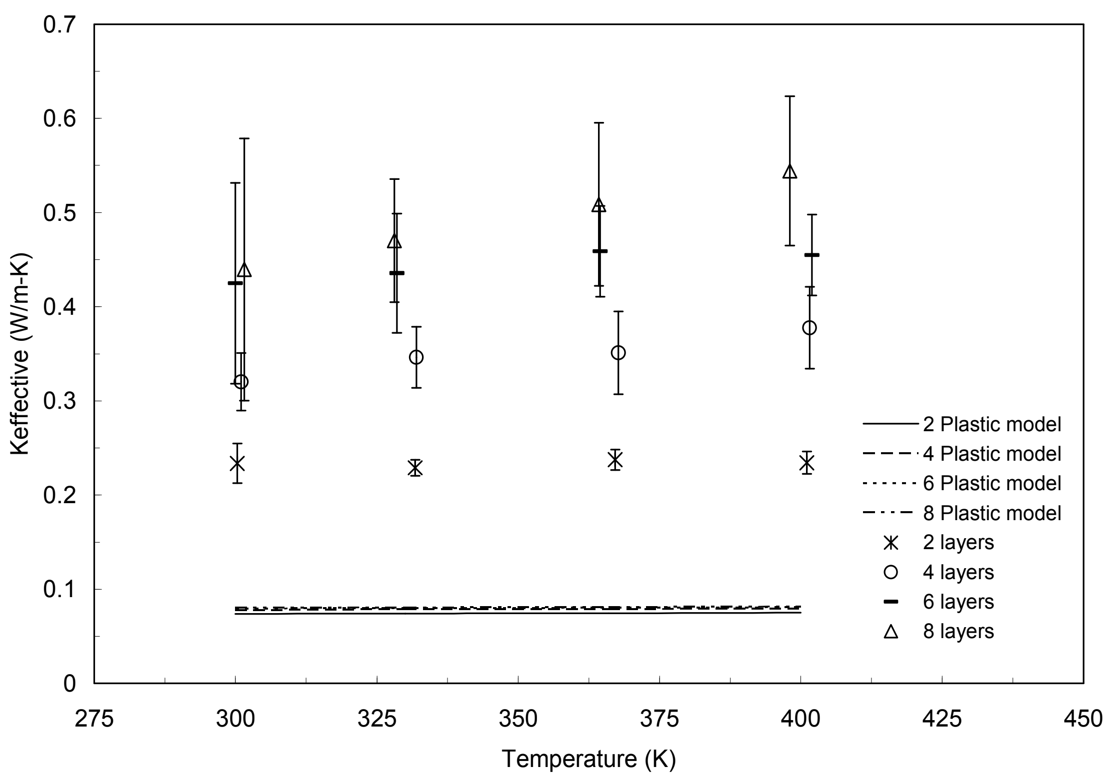

Fig. 18. Effective thermal conductivity of multiple wire mesh layers and predicted values using plastic micro contact model as a function of upper interface temperature

The comparisons made above represent an attempt to verify the experimental results gathered in the investigation. However, due to the previously described limitations of models significantly underestimating liner contributions, the calculated results cannot be definitively verified, as was the intent of the study. However, in contrasting the models with the observed experimental results, some important questions are raised with regard to the relevance of the liner to the overall thermal performance of the proposed insulation scheme. In selecting a historically poor insulation material, galvanized steel, it became a significant challenge to negate its bias toward promoting a high degree of heat transfer.

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 results show 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 constituting layers must independently exhibit similar insulating properties. Otherwise there may be an equalization of thermo-physical properties between the constituents, as was seen with the effective thermal conductivity of the wire mesh and liner composite structure.

6.11 Comparison of the effective thermal conductivity of proposed insulation scheme with existing insulation technologies

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 3 and 4 are 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 its thermal performance is noticeably inferior. Even considering the best performing wire mesh and hollow glass microsphere case, its effective thermal conductivity ranges from 3-10 times that of conventional insulation materials. However, selection of an insulation system is an complex process based on many factors beyond the scope of this study, with thermal conductivity being merely one component. This will become more apparent upon considering some advantages and disadvantages associated with the proposed design.

Table 3
Thermal conductivity of proposed insulation along with some conventional materials at 300K [24]

Material	Wire Mesh & Hollow Glass Microsphere	Air	Fiber Glass	Wood Wool	Mineral Wool
Thermal Conductivity (W/m-K)	0.22 ~ 0.65	0.0263	0.032 ~ 0.050	0.068	0.036

Table 4
Thermal conductivity of other conventional insulation materials at 300K [24]

Material	Rock Wool	Poly-ethylene	Poly-urethane	Expanded Polystyrene	Extruded Polystyrene
Thermal Conductivity (W/m-K)	0.034 ~ 0.041	0.062	0.023	0.035 ~ 0.046	0.039

6.12 Advantages

The primary advantage in using a metallic wire mesh-based insulation system is 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 to non-metal based insulation systems. In particular, materials with superior compressive strengths, along with fair insulating properties, may have uses as deep sea or underground piping insulation. In addition, high temperature thermal insulation applications at 400K-1000K, become possible specifically with ferrous or nickel-based alloys, even some exhibiting noticeably lower thermal conductivity at higher temperatures.

There are also many cases where insulations are subject to cyclical thermal loading, where thermal expansion of the materials becomes critical. Polymeric insulations in general tend to be more susceptible to thermal fatigue then are metals, especially given the multilayer designs common in today's insulation systems. Polymers, being an organic material, are also more susceptible to combustion than their non-organic counterparts, thus limiting their use in certain applications where safety is of utmost importance.

Lastly, metallic wire mesh-based insulations will tend to be sleeker in design due to weight considerations, with potential impacts 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 HVAC systems.

6.13 Disadvantages

The primary concern in the use of the proposed design is in its thermal performance characteristics, thermal conductivity in particular. A metallic-based insulation will have to exhibit insulating properties approaching their non-metallic counterparts to be considered viable as a conduction barrier. Should this condition be satisfied, secondary concerns involving insulating system integration and failure modes can be evaluated.

With respect to the incorporation of wire mesh-based insulations to existing systems, several hurdles must be overcome. 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 and inertia of technology acceptance. Consequently it requires more then superior technology, which at this point cannot be said of wire mesh/hollow glass microsphere composite structures, to supplant existing insulation schemes.

Even given 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 on the market numerous technological concepts that were never adopted, not because they did not represent superior performance, but because the required capital structure 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 the market may deem unnecessary.

Challenges regarding possible failure modes of wire mesh-based insulations 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, while 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.

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 non-metal. The mechanisms for degradation may vary but the outcomes are not favorable in any case. Thus metallic wire mesh-based insulations offer negligible improvement in this particular area.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary of findings

This paper investigates the use of multiple layers of metallic wire-screen mesh, each separated by a liner, with hollow glass micro-spheres as filler material, for the purpose of thermal insulation. The findings of the experimental investigation are as follows:

- As shown by the present experimental data, as the number of wire mesh layers increased, their influence on the effective thermal conductivity value became more significant.
- In most cases, addition of hollow glass spheres as filler material resulted in statistically insignificant effects on effective thermal conductivity.
- Addition of hollow glass microspheres as filler material at best rendered the insulation unchanged in terms of effective thermal conductivity for four, six and eight layers of wire mesh. For one particular instance, it adversely affected the two layer wire mesh insulation by increasing the effective thermal conductivity.
- Concrete evidence concerning heat losses could not be definitively obtained, but based on detailed visual observations (e.g., test runs under vacuum), no noticeable alteration of thermal behavior occurred. This signifies that heat transfer during the experiments was confined to the insulation structure, *i.e.* metallic wire mesh, liner and hollow glass microspheres.

- Comparison of the proposed insulation scheme to several common insulation materials indicated substandard thermal performance, with effective thermal conductivity ranging from 3 to 10 times higher.
- In contrasting experimental results with a previously developed model, it was reasoned that the model, developed as an extension of a single layer formulation, lacked crucial aspects pertaining to its derivation (e.g., thermal spreading of the liner). As a result, the liner's contribution to the overall heat transfer was underestimated, leading to the models' consistently under-predicting when compared with actual observed results, while also failing to identify separation in effective thermal conductivity as a function of wire mesh layers.

7.2 Conclusions and recommendations

The relevant conclusions, supported by findings detailed above, can be summarized as follows:

- Multiple layer metallic wire mesh-based insulations, as tested, are inferior in thermal performance when compared to chemical-based thermal insulations currently available on the market.
- Addition of hollow glass microspheres as filler material into the wire mesh results in negligible improvement of the thermo-physical properties as a thermal insulator.

- The insulating thermal performance of wire meshes, with sizes and configurations that yield no free convection in the cavities, cannot be improved by introducing filler materials with thermal conductivities higher than that of air.

The following will outline recommendations for further studies and possible remedies regarding use of a metallic wire mesh-based insulation:

1) Investigate the use of a liner material exhibiting good insulating properties on par with the wire mesh independently.
2) Investigate the use of coatings on the wire mesh or liner to increase thermal resistance.
3) Establish innovative means of separating the various layers in order to minimize hypothesized thermal spreading effects in existing liner.
4) Apply materials selection criteria to yield best possible performance given current design.
5) Investigate a wider range of testing conditions with respect to temperature and pressure. Thermal performance may become more competitive with respect to cryogenic applications or at very high temperature and pressure, as in deep sea oil exploration.

REFERENCES

[1] F.P. Incropera, D.P DeWitt, Fundamentals of Heat and Mass Transfer 5th ed., John Wiley & Sons Inc, New York, NY, 2001, p. 588.

[2] J.F. Hou, H.B. Bai, D.W. Li, Damping capacity measurement of elastic porous wire-mesh material in wide temperature range, J. Materials Processing Technology 206 (1-3) (2008), 412-418.

[3] J. Xu, J. Tian, T.J. Lu, H.P. Hodson, On the thermal performance of wire-screen meshes as heat exchanger material, Int. J. Heat Mass Transfer 50 (5-6) (2007) 1141-1154.

[4] M.K. Mittal, L. Varshney, Optimal thermohydraulic performance of a wire mesh packed solar air heater, Solar Energy 80 (9) (2006) 1112-1120.

[5] P. Riva, A. Franchi, Behavior of reinforced concrete walls with welded wire mesh subjected to cyclic loading, Structural Journal 98 (3) (2001) 324-334.

[6] L. Rayleigh, On the influence of obstacles arranged in rectangular order upon the properties of a medium, Philos. Mag. LVI (1892) 481-502.

[7] C.T. Hsu, K.W. Wong, P. Cheng, Effective stagnant thermal conductivity of wire screens, AIAA J. Thermophys. 10 (3) (1995) 542-545.

[8] E.G. Alexander Jr., Structure-Property Relationships in Heat Pipe Wicking Materials, Ph.D. Dissertation (1972), Department of Chemical Engineering, North Carolina State University, Raleigh, NC.

[9] J.H. Van Sant, J.R. Malet, Thermal conductivity of some heat pipe wicks, Letters in Heat and Mass Transfer 2 (1975) 199-206.

[10] W.S. Chang, Porosity and effective thermal conductivity of wire screens, J. Heat Transfer 112 (5) (1990) 5-9.

[11] Chen Li, G.P. Peterson, The effective thermal conductivity of wire screen, Int. J. Heat Mass Transfer 49 (21-22) (2006) 4095-4105.

[12] D.K. Kim, C. Silva, E. Marotta, L.S. Fletcher, Characterization/modeling of wire screen insulation for deep-water pipes, J. Thermophysics Heat Transfer 21 (1) (2007) 0887-8722.

[13] D.K. Kim, An Analytical and Experimental Investigation for an Interstitial Insulation Technology, Ph.D. Dissertation (2008), Department of Mechanical Engineering, Texas A&M University, College Station, TX.

[14] R. Wawryk, J. Rafalowicz, Heat transfer in microsphere insulation, J. Thermal Analysis 34 (1) (1988) 249-257.

[15] S. M. Aceves, G. D. Berry, G. D. Rambach, Insulated pressure vessels for hydrogen storage on vehicles, Int. J. Hydrogen Energy 23 (7) (1998) 583-591.

[16] P. Mueller, T. Durrant, Cryogenic propellant liquefaction and storage for a precursor to a human Mars mission, Cryogenics 39 (12) (1999) 1021-1028.

[17] D.K. Kohli, R.K. Khardekr, R. Singh, P.K. Gupta, Glass micro-container based hydrogen storage scheme, Int. J. Hydrogen Energy 33 (1), IWHE 2006, (2008) 417-422.

[18] C. L. Tien, G. R. Cunnington, Glass microsphere cryogenic insulation, Cryogenics 16 (10) (1976) 583-586.

[19] R. Wawryk, J. Rafalowicz, K. Balcerek, The influence of microsphere diameter on the coefficient of thermal conductivity of microsphere insulation, Cryogenics 23 (8) (1983) 441-443.

[20] Expandable microspheres for weight reduction in PVC, SBS and EVA, Additives for Polymers (8) (2003) 3-4.

[21] 3M Specialty Additives, Microspheres Thermal Conductivity Report. St. Paul, MN (1998) p. 1.

[22] F. Ochs, W. Heidemann, H. Muller-Steinhagen, Effective thermal conductivity of moistened insulation materials as a function of temperature, Int. J. Heat Mass Transfer 51 (3-4) (2008) 539-552.

[23] S.J. Kline, F. A. McClintock, Describing uncertainties in single-sample experiments, Mechanical Engineering 75 (1) (1953) 3-8.

[24] A.A. Abdou and I.M. Budaiwi, Comparison of thermal conductivity measurements of building insulation materials under various operating temperatures, J. Building Physics 29 (2005) 171-184.

APPENDIX A

SAMPLE CALCULATIONS

A walkthrough of the typical calculations performed in the investigation will be conducted on the two layer case with air as filler under ambient conditions at approximately 300K upper interface temperature. Upon reaching steady state a text file is created, via the integrated LabView software, that contains the temperature profile found in the upper and lower flux meters, to be used for calculations. Table A lists the temperature found in each of the eight thermocouples when a steady state condition is reached, to be used for further analysis. With the aid of Microsoft Excel® using linear regression analysis, the slopes and intercepts for both the upper and lower flux meters are found, with temperature throughout the flux meter a linear function of position. For this particular instance the results are as follows:

$$T_{upper} = -9.66X_{upper} + 301\text{ K}$$

$$T_{lower} = -15.0X_{lower} + 283\text{ K}$$

Table 5
Applicable output from the experiments, including temperature at each thermocouple along with their respective positions, upon reaching steady state condition

TC#	Avg. Temp(K)	X (m)
1	300.70	0
2	300.64	0.00635
3	300.58	0.0127
4	300.52	0.01905
5	282.71	0.04819
6	282.62	0.05454
7	282.54	0.06089
8	282.42	0.06724

Fourier's Law is now used to calculate the heat fluxes through the upper and lower flux meters. Thermal conductivity of the standardized NIST electrolytic iron flux meters is readily available as a function of temperature. Knowing the temperature gradients from the slopes previously obtained through linear regression of the flux meters, calculations are as follows:

$$q''_{upper} = -k_{fluxmeter} \frac{dT}{dx}_{upper} = -78.14 \times -9.66 = 754.8 \ \frac{\mathrm{W}}{m^2}$$

$$q''_{lower} = -k_{fluxmeter} \frac{dT}{dx}_{lower} = -79.71 \times -15.0 = 1195.7 \ \frac{\mathrm{W}}{m^2}$$

Taking the average of the heat fluxes:

$$q'' = \frac{1}{2}\left(q''_{upper} + q''_{lower}\right) = \frac{1}{2}\left(754.8 + 1195.7\right) = 975.25 \ \frac{\mathrm{W}}{m^2}$$

Now, knowing the positions of the upper and lower interfaces along with the two regression equations, the temperature drop across the test sample can be calculated.

$$T_u^* = -9.66 X_{upper} + 301 = -9.66 \times 0.03155 + 301 = 300.7 \text{ K}$$

$$T_l^* = -15.0 X_{lower} + 283 = -15.0 \times 0.03569 + 283 = 282.5 \text{ K}$$

$$\Delta T = T_u^* - T_l^* = 300.7 - 282.5 = 18.2 \text{ K}$$

Finally the effective thermal conductivity is determined using the known thickness of the test sample, along with previous calculated results.

$$k_{effective} = \frac{q'' t_{insulation}}{\Delta T} = \frac{975.25 \frac{W}{m^2} \times 0.00414 \ m}{18.2 \ K} = 0.222 \frac{W}{m \cdot K}$$

APPENDIX B

UNCERTAINTY ANALYSIS

The uncertainty associated with the calculated effective thermal conductivity is found using the Klein- McClintock procedure where, given:

$$R = f\left(x_1, x_2, x_3, \ldots, x_n\right)$$

The uncertainty associated with the function can be described by

$$w_R = \left[\left(\frac{\partial R}{\partial x_1} w_{x_1}\right)^2 + \left(\frac{\partial R}{\partial x_2} w_{x_2}\right)^2 + \ldots + \left(\frac{\partial R}{\partial x_n} w_{x_n}\right)^2\right]^{\frac{1}{2}}$$

The relative uncertainty can be found by simply dividing the uncertainty by the original equation. The function of interest is that where the effective thermal conductivity is calculated.

$$k_{effective} = \frac{q'' t_{insulation}}{\Delta T}$$

The partial derivatives of the effective thermal conductivity with respect to each value are as follows:

$$\frac{\partial k_{effective}}{\partial q''} = \frac{t_{insulation}}{\Delta T} \qquad \frac{\partial k_{effective}}{\partial t_{insulation}} = \frac{q''}{\Delta T} \qquad \frac{\partial k_{effective}}{\partial \Delta T} = -\frac{q'' t_{insulation}}{\left(\Delta T\right)^2}$$

Substitution into the uncertainty equation yields the following:

$$w_{k_{effective}} = \left[\left(\frac{t_{insulation}}{\Delta T} w_{q''}\right)^2 + \left(\frac{q''}{\Delta T} w_{t_{insulation}}\right)^2 + \left(-\frac{q'' t_{insulation}}{\left(\Delta T\right)^2} w_{\Delta T}\right)^2\right]^{\frac{1}{2}}$$

Some simple algebraic manipulation is needed in order to generate the relative uncertainty equation.

$$\frac{w_{k_{effective}}}{k_{effective}} = \left[\left(\frac{w_{q''}}{q''} \right)^2 + \left(\frac{w_{t_{insulation}}}{t_{insulation}} \right)^2 + \left(\frac{w_{\Delta T}}{\Delta T} \right)^2 \right]^{\frac{1}{2}}$$

This does not represent the final relative uncertainty equation, as there exist terms that may be simplified further. The relative uncertainty of the insulation thickness can be found readily from the measurement devices used, but average heat flux as well as the temperature drop relative uncertainties must be reduced to terms that were measured or can readily be calculated. Starting with the heat flux uncertainty, the same Kline-McClintock procedure is used on the following equation:

$$q'' = \frac{1}{2}\left(q''_{upper} + q''_{lower} \right)$$

Using Fourier's Law allows substitution of the upper and lower heat fluxes giving:

$$q'' = -\frac{1}{2}\left(k_{upper} \frac{dT}{dx}_{upper} + k_{lower} \frac{dT}{dx}_{lower} \right)$$

The upper and lower temperature gradients are simply the slopes in the linear regression of the upper and lower flux meter temperature profiles denoted by m_u and m_l.

$$q'' = -\frac{1}{2}\left(k_{upper} m_u + k_{lower} m_l \right)$$

The partial derivative of the average heat flux with respect to each variable is as follows:

$$\frac{\partial q''}{\partial k_{upper}} = -\frac{1}{2} m_u \qquad \frac{\partial q''}{\partial m_u} = -\frac{1}{2} k_{upper} \qquad \frac{\partial q''}{\partial k_{lower}} = -\frac{1}{2} m_l \qquad \frac{\partial q''}{\partial m_l} = -\frac{1}{2} k_{lower}$$

The relative uncertainty of the average heat flux can now be expressed in terms of readily calculable and/or obtainable values. With modest algebraic manipulation and assuming uniform uncertainty in the thermal conductivity of the standardized NIST upper and lower flux meters, denoted $w_k = w_{k_{upper}} = w_{k_{lower}}$, the relative uncertainty of the average heat flux is given by:

$$\frac{w_{q''}}{q''} = \left[\frac{\left(k_u w_{m_u}\right)^2 + \left(k_l w_{m_l}\right)^2 + \left(m_u^2 + m_l^2\right) w_k^2}{k_{upper} m_u + k_{lower} m_l} \right]^{\frac{1}{2}}$$

The final piece needed to calculate the relative uncertainty of the effective thermal conductivity is the relative uncertainty associated with the temperature drop across the test sample. Here the Kline-McClintock procedure is performed on the following equation:

$$\Delta T = T_u^* - T_l^*$$

With the following result for relative uncertainty:

$$\frac{w_{\Delta T}}{\Delta T} = \left[\frac{w_{T_u^*}^2 + w_{T_l^*}^2}{\left(T_u^* - T_l^*\right)^2} \right]^{\frac{1}{2}}$$

Finally substituting the relative uncertainties of the average heat flux and temperature drop into that of the effective thermal conductivity yields:

$$\frac{w_{k_{effective}}}{k_{effective}} = \left[\frac{(m_u^2 + m_l^2) w_k^2 + (k_{upper} w_{m_u})^2 + (k_{lower} w_{m_l})^2}{(k_{upper} w_{m_u} + k_{lower} w_{m_l})^2} + \frac{w_{T_u^*}^2 + w_{T_l^*}^2}{(T_u^* - T_l^*)^2} + \left(\frac{w_{t_{insulation}}}{t_{insulation}} \right)^2 \right]^{\frac{1}{2}}$$

This equation represents the relative uncertainty associated with each calculated effective thermal conductivity value used throughout the investigation.

VITA

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