SIMULATION OF THE HEAT TRANSFER THROUGH FIBROUS INSULATION

Andrew Webley[1], Liu Yang[2] and David Nash[3]
[1]Mechanical and Aerospace Engineering, University of Strathclyde,
75 Montrose St, Glasgow, United Kingdom
Email: andrew.webley@strath.ac.uk
[2] Mechanical and Aerospace Engineering, University of Strathclyde,
75 Montrose St, Glasgow, United Kingdom
Email: l.yang@strath.ac.uk
[3] Mechanical and Aerospace Engineering, University of Strathclyde,
75 Montrose St, Glasgow, United Kingdom
Email: d.nash@strath.ac.uk

Keywords: Fibrous insulation, simulation, heat transfer

Abstract

The aim of the research is to produce a simulation of fibrous thermal insulation, so that the overall thermal conductivity of the insulation can be predicted. This allows the thermal conductivity of the insulation to be determined, and the optimum fibre layup can be investigated. In order to ensure the model is behaving correctly, it was compared to the thermal conductivity of a glass fibre blanket. This blanket was produced using the needle-punch technique, and so was made largely of in-plane randomly orientated fibres with regular out-of-plane fibres extending through multiple fibre layers and holding all the fibre layers together. The geometry was generated using MATLAB, before being converted into a 3D CAD model using ANSYS APDL, with the finite element analysis being carried out using ANSYS Workbench. The results of the simulation give an overall thermal conductivity that is very close to the experimentally measured thermal conductivity. As a result, the simulation can be considered to be accurate for at least some fibre orientations.

1. Introduction

Thermal insulation is used in a wide range of industries in order to reduce the amount of heat transfer occurring. The oil and gas industry uses thermal insulation around their undersea oil-pipelines to keep the oil warm enough that it flows through the pipe [2]. Flexible insulation is attractive for this use since it makes attaching the insulation to the pipeline much easier, and it maximises the contact between the insulation and the pipeline [3].

The aim of the research is to produce a polymer aerogel and glass fibre composite, where the polymer aerogel ensures the thermal conductivity is very low, typically below 20mW/mK while the glass fibres adding a degree of mechanical flexibility to the composite so that it can be used to wrap around cylindrical pipes as thermal insulation. The heat transfer through the composite occurs in three ways: solid conduction, gas conduction and radiation. The narrow size of the pores in the composite, or even in the glass fibre blanket alone, means that there is no bulk movement of the fluid in the pores and so there is no convection in the fluid [4, 5]. The gas can be treated as a solid in this case, and only the conduction through the gas needs to be taken into account. Since the insulation is planned to be used with relatively small temperature differences, around 100°C at most, the radiative heat transfer is typically fairly small compared to the solid and gas conductive heat transfers [4].

In this paper, an initial model of the glass fibres present in the composite is presented, as well as the experimental data required to ensure that the computer model is accurately modelling the glass fibre mat that will be used to produce the composite.

2. Modelling

2.1. Geometry

In order to take into account the random nature of the fibres, it is important to allow some parameters of the geometry to be randomly selected. The fibre orientation and size are randomly selected, based on measurements of the glass fibre blanket and the predicted distribution of the variations. The values used to generate the geometry are shown in Table 1, with the generation process being based on the method used in [6]. Each individual fibre is lowered into the bounding region until it reaches the bottom of the region or collides with another fibre, and is then clipped using either a 2D or 3D clipping algorithm [7,8] depending on whether the fibre is horizontal or not. In addition, if the post-clipping length is less than 1/5 of the average fibre length, then the fibre is deleted. This is done because very short fibres force a dense mesh on the fibre, which significantly increases the length of time required to both mesh the geometry and run the simulations, while also not contributing significantly to the heat transfer, as they are likely to be in contact with at most one other fibre. After the fibres have been generated, all of the fibre diameters are increased to 1.05 times the original diameter. This increases the size of the contact location, which reduces the very large heat transfers that the simulation would produce at a point contact between two cylinders. While this makes the fibre geometry slightly less representative of the actual fibre geometry, it also improves the simulation accuracy, particularly near the contact areas.

One of the major limitations of the model is that the solid volume fraction is effectively uncontrolled, and can only be indirectly controlled by changing the fibre angles, fibre diameter/length and bounding region size. In order to measure the volume fraction, a Monte Carlo approach is used. This generates a large number of random points within the bounding region, and then determines whether the point is within a fibre or not. The ratio of points within fibres to total generated points is the volume fraction for the composite. In these simulations, this is run until the relative difference between two consecutive runs is less than $1x10^{-5}$, with the target volume fraction being 3-10%.

The other main limitation of the model is that the fibres produced have to be straight cylinders. This means that in cases where the fibres are partially melted together, or are bent around other fibres, the model cannot capture the details fully. By changing the amount of increase to the diameter used, the effect of fibres melting together can be captured, unless there are significant changes to the shape of the fibres at the contact area.

Table 1. The fibre properties

Parameter	Value
Fibre diameter	12µm
Fibre length	2cm
In-plane angle range	0° to 180°
Fibre thermal conductivity	850mW/mK
Air thermal conductivity	24mW/mK
Fibre volume fraction	3.4%
Bounding region	1cm

2.2. Simulation

In order to run the simulation, the system first has to be meshed. Due to the random positioning of the fibres, using consistent mesh settings is impossible, as some geometries will be unable to mesh, or mesh with an overly dense mesh, using the same settings that produced satisfactory results for other geometries. A coarse mesh was used for the bounding region since the fibres are the main source of complexity, although the mesh became denser near the fibres.

The top and bottom of the bounding region were held at fixed temperatures, and the other sides of the bounding region were marked as perfect insulation to ensure the heat transfer was as one dimensional as possible.

3. Thermal Conductivity Measurement

In order to validate the thermal simulation, a Netzsch Heat Flow Meter HFM 436/3/1E was used to measure the thermal conductivity of a glass fibre blanket, with the simulation aiming to model a glass fibre geometry that is representative of the glass fibre blanket. This required the use of a 30cm by 30cm square of the glass fibre, with a thickness of 1cm. As this would involve a very large number of fibres, the simulation version used a significantly smaller geometry of the same thickness.

The results of this gave a thermal conductivity value of 34mW/mK for the glass fibre blanket for a temperature difference of 80°C to 4°C.

4. Results and Discussion

The heat flux results from the simulation are shown in
Figure 1. The simulation included the air around the fibres, with the air being treated as a stationary surrounding material. This means that conduction can occur between the fibres and the air, but there is no convective heat transfer. While the maximum heat transfer is very large, this is due to singularities in the simulation occurring at the fibre-fibre contact regions, as seen in
Figure 2.

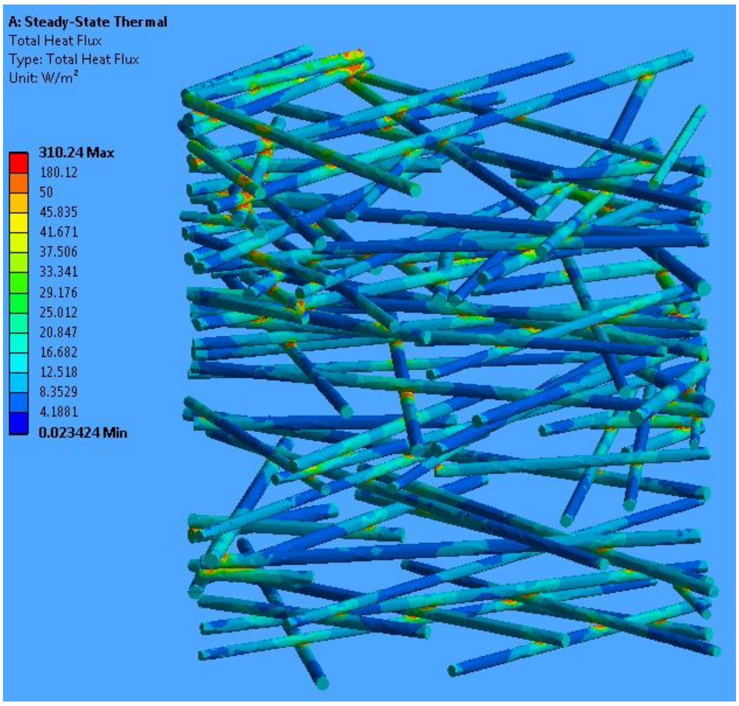

Figure 1. The heat flux distribution in the fibrous phase, with the air being hidden

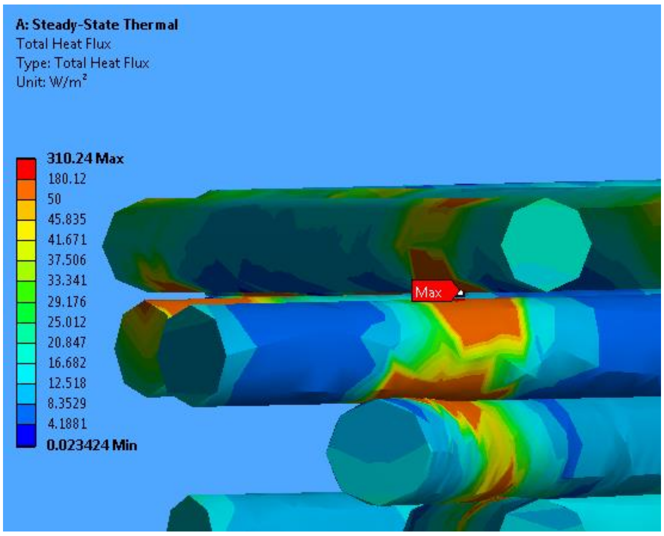

Figure 2. Zoomed in region showing where the highest heat transfer occurs

In order to determine the overall thermal conductivity, an average heat flux value for the simulation was determined. The maximum and minimum total heat transfers for the upper and lower surfaces of the air box were determined, and an average heat flux was obtained from these values, as shown in Table 2. This means that Fourier's law can be applied with the assumption of one-dimensional heat transfer to determine the thermal conductivity, since the representative length, heat flux and temperature difference are known. This gives a thermal conductivity value of 39 mW(mK)$^{-1}$, which is very close to the actual thermal conductivity of the glass fibre blanket, which was 34 mW(mK)$^{-1}$. The glass fibre blanket has a volume fraction of 4%, which was measured by comparing the density of the blanket to the density of a glass fibre, which means that the geometry used in the simulation featured a slightly lower volume fraction than the actual blanket does.

Table 2. The heat flux values obtained from the simulation.

Surface	Heat Flux ($W(m^{-2})$)		
	Minimum	Maximum	Average
Upper	0.63	13	6.8
Lower	3.6	6.9	5.3
Overall	N/A	N/A	6.05

5. Conclusions

It can be seen that the geometry can be produced fairly simply, while also providing accurate results. The overall highest heat flux value is significantly larger than expected, but is due to a coarse mesh being present at the fibre-fibre intersections, leading to exaggerated heat flux values at that point. The values for the thermal conductivity are very close to the expected value, while also being slightly higher than the measured value.

Acknowledgments

This work has been financially supported by Blueshift International Materials and by the Energy Technology Partnership Scotland.

The support of the laboratory technicians at the University of Strathclyde has been invaluable in the obtaining of experimental data to validate the computer model.

References

[1] Manufacturing S. E-Glass 650 Thermal Needlemat Data Sheet.
[2] G.J. Zabaras and J. Zhang. Steady-State and Transient Thermal Performance of Subsea Hardware. *SPE Drilling & Completion,* 13:108-113, 1998.
[3] S. Denniel and C. Blair. Aerogel Insulation For Deepwater Reelable Pipe-in-Pipe. *Offshore Technology Conference, Houston, Texas,* May 3-6 2004.
[4] S.S. Woo, I. Shalev, and R.L. Barker. Heat and Moisture Transfer Through Nonwoven Fabrics. *Textile Research Journal*. 64: 149-62, 1994.
[5] V.A. Petrov. Combined radiation and conduction heat transfer in high temperature fiber thermal insulation. *International Journal of Heat and Mass Transfer*. 40: 2241–7, 1997.
[6] R.T. Arambakam, H. Vahedi, and B. Pourdeyhimi. A simple simulation method for designing fibrous insulation materials. *Materials & Design*. 44: 99–106, 2013.
[7] Y.-D. Liang and B. A. Barsky A New Concept and Method for Line Clipping. *ACM Transactions on Graphics*. 3: 1-22, 1984.
[8] R. Kodituwakku, K.R. Wijeweera, and M.A.P. Chamikara. An Efficient Line Clipping Algorithm for 3D Space. *International Journal of Advanced Research in Computer Science and Software Engineering*. 2: 96-101, 2012.