Modeling heat transfer through Filament Yarns by Random Geometry Creation

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Abstract

Filament yarns are a collection of fibers of set diameter and material held together by tension and/or intra-filament attraction. This results in a stacking pattern that can be random with different degrees of freedom. Slight changes in tension or friction may result in a different arrangement of the microfibers in the cross-section, where the space between the fibers is filled with air. Hence, the effective thermal conductivity of the yarn would be a function of the arrangement pattern of the microfibers. We have devised a random geometry creation model in COMSOL using model methods to create random arrangements of microfibers. We vary the influencing variables while enforcing geometrical constraints and then determine the effective thermal conductivity of the yarn. The simulation then calculates the extent of the dependence of the effective thermal conductivity of the yarn cross section on different parameters.

Introduction

Modeling of heat transfer often deals with the introduction of phenomenological quantities (e.g. effective thermal conductivity[1], time constants[2]) and non-dimensional numbers[3]. Heat transfer in porous media is modeled extensively using effective thermal conductivity for systems one or two or all the three modes of heat transfer. The need for using a phenomenological quantity arises because of various external parameters influencing the heat transfer in the porous medium, such as a packed bed. These can be the porosity of the medium, wall friction, viscosity of the flow, density of the flowing media, radiation shape factors, surface roughness of the particles, contact angles between the particles, coordination numbers etc.[4]–[7]. The surface roughness between the wall and between the particles themselves have also been defined through various tribological models[1], [5], [8]. Yarns and fabrics are perhaps the most common porous media known to mankind. In recent years thermal and structural properties of different kinds of yarns have become a point of focus for research. We introduce one such type of yarn, known as filament yarn, which is a grouping of a bunch of cylindrical microfibers (or filaments) arranged in a random pattern. In this paper we describe how we utilized COMSOL Multiphysics' features to model filament yarns by random geometry creation and determine the effective thermal conductivity of the yarn's cross-section.

Theory

As mentioned earlier, filament yarns are a collection of randomly distributed cylindrical microfibers, with varying or same cross sections. The random distribution of the microfibers and the diameter of the yarn are both dependent upon the axial tension or lateral compression applied upon the yarn. Hence, the cross-sectional arrangement of the yarn, with random distribution of the microfibers becomes very crucial in order to obtain a measure of structural or thermal properties.

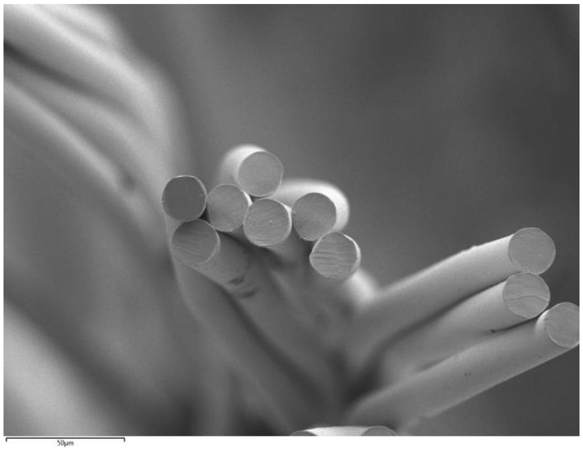

Figure 1 SEM image of 34 filament yarn

Figures 1 and 2 are the SEM images of two such commercially available filament yarns. The yarns have filaments of diameter 20 microns and have 34 and 68 filaments per yarn respectively. The filaments have almost circular cross section.

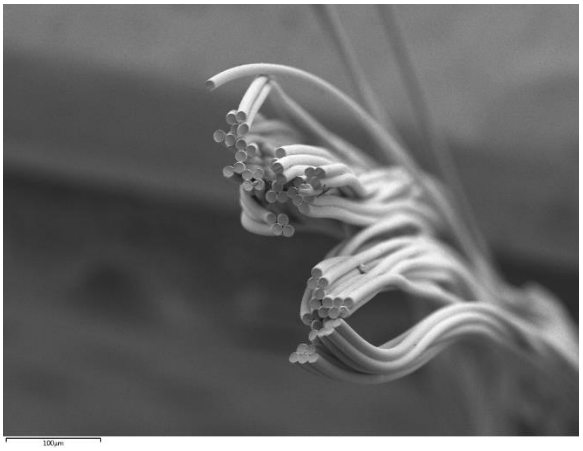

Figure 2 SEM Image of 68 filament yarn

The thermal conduction through a medium is modeled using Fourier's law, and can be represented in equation form as:

$$q = -k \nabla T$$

Where q is the heat flux through the medium (W/m^2), k is the thermal conductivity of the material (W/m-K) and T is the temperature (K). A two-dimensional setup is required since we are interested in modeling the thermal conductivity of the yarn cross sections. For general two-dimensional cross-sections with a porous media enclosed in between two walls, the setup looks like:

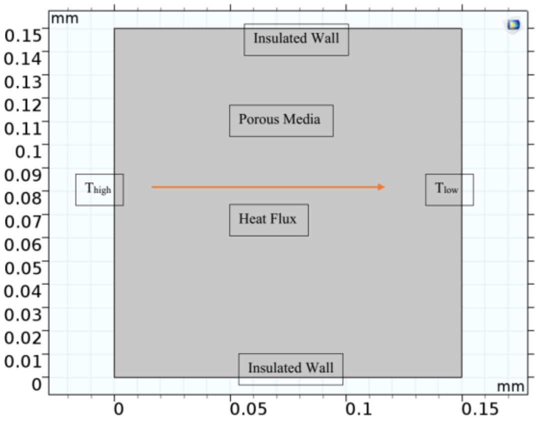

Figure 3 Simple setup for 2-D conduction

To determine the effective thermal conductivity of the cross section in one direction, we need to impose thermal boundary conditions such that there is no heat flux in the other direction. This is shown in Figure 3, where the heat flux flows in the x direction from the higher temperature wall to the lower temperature wall. The heat flux in the x direction and the temperature difference between the walls can then be used to determine the effective thermal conductivity as:

$$k_{eff} = q_x \times \frac{L}{\Delta T}$$

where L is the diameter of the yarn or the principal dimension of the yarn cross section. The effective thermal conductivity here is a phenomenological property and not the physical property and is dependent upon the packing fraction, the thermal conductivities of the packing materials, or geometrical factors.

To model the thermal conductivity of these yarns through its cross section, we need to develop accurate models to simulate the microstructure, or the arrangement of the microfibers. This can be achieved through random geometry creation, by applying structural constraints on the geometry. This is explained in the next section.

Simulation Methodology & Algorithm

In this section we introduce an algorithm to generate the random packing. We utilized COMSOL's inbuilt feature of model methods, to code this algorithm. The total domain of the cross section would be the diameter of the yarn, varying it would result in denser or rarer packing of microfibers. The algorithm must follow the following constraints in order for the system to not violate laws of physics:

a.) The distance between the centers of any two microfibers cannot be less than the diameter, i.e. the microfibers can at most have a point contact.

b.) The distance between the center of any microfiber and the yarn wall should be more than or equal to the radius, i.e. the microfiber can at most have a point contact with yarn wall.

c.) The center of the microfibers should lie completely between the walls of the yarn.

Figure 4 shows the schematic of the developed algorithm, and figures 5 and 6 show the random geometry obtained from the model method, as run for the 34 and 68 filament yarns. The algorithm satisfies the three constraints identified above.

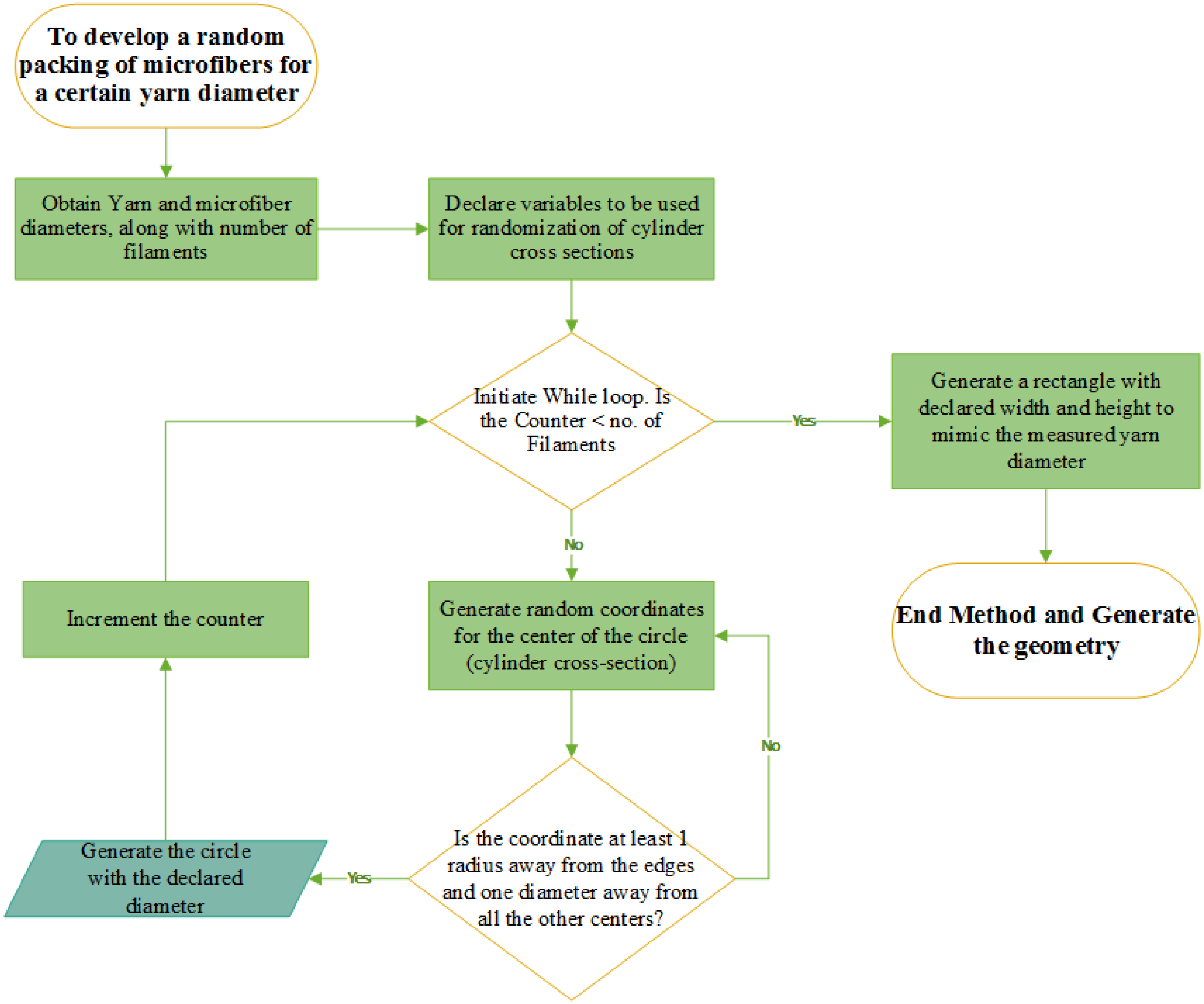

Figure 4 Flowchart of the model method

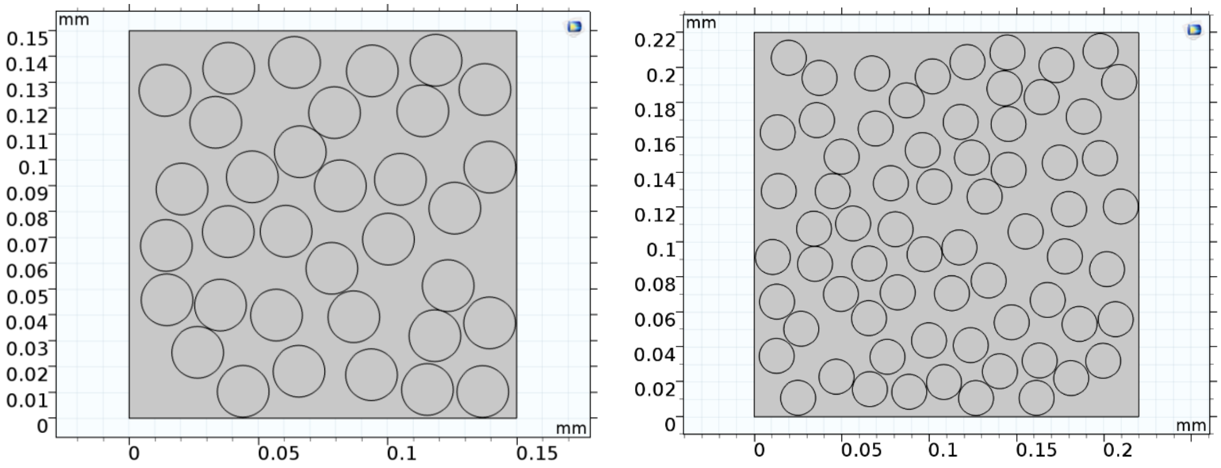

Figure 5 Random packing of 34 and 68 filament yarns for yarn diameter of 0.15mm & 0.22mm respectively

Simulation Results

The simulations for the effective thermal conductivity were performed for two yarns with 34 and 68 filaments. The filaments (or microfibers) have the same circular cross section in both the yarns. It is observed experimentally and illustrated in published literature that yarns and fabrics in general have a packing fraction between 0.2 & 0.55 [9]–[11]. There may be some cases where this threshold is breached, however, in this paper we are well within the limit. In order to capture the effect of the random packing, the simulations are run 20 times at each packing fraction level, and the thermal conductivities are calculated. The packing fraction of the yarns are varied between 0.4 and 0.5 by changing the diameter of the yarn, i.e. the edge of the square. Figure 6 shows the surface temperature profile for two different packing fractions each for 34 and 68 filament yarns, with a certain random packing arrangement at that packing fraction.

Figures 7 and 8 demonstrate the variation between the effective thermal conductivities for different run indices, at the same porosity for 34 and 68 filament yarns. It can be noted that there is almost a 10% variation between the calculated effective thermal conductivities at the same packing fraction. This may or may not be significant depending upon the kind of precision needed. Figure 9 illustrates the evolution of the average effective thermal conductivity with packing fraction for both yarns. The error bars indicate the standard deviation, which may not be very significant for an individual case. However, the deviation has the potential to significantly bridge the gap between the average effective thermal conductivities for proximal packing fraction levels. Hence, if the jump in packing fraction is large, it is safe to conclude that the packing fraction is the most dominant factor influencing thermal transport.

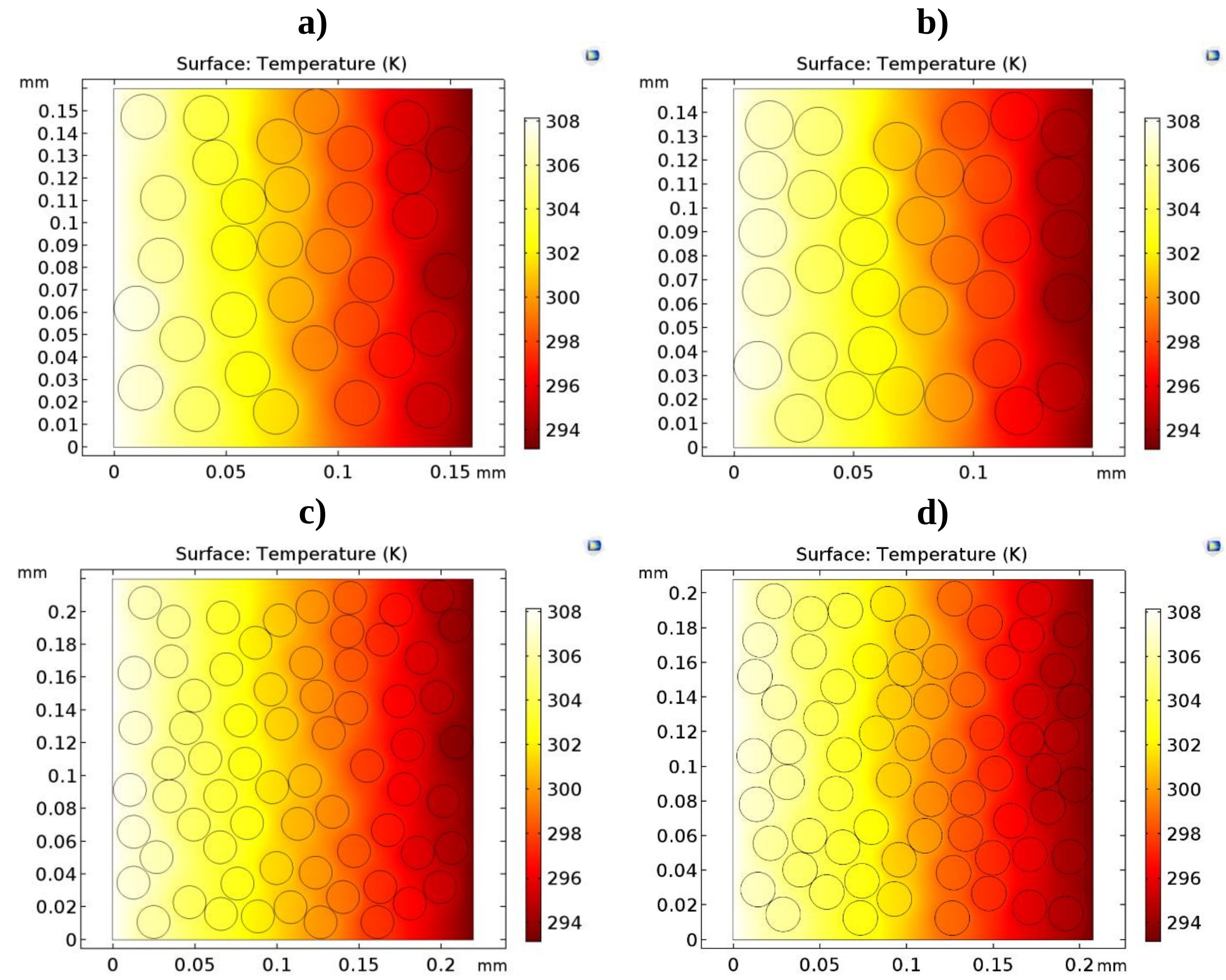

Figure 6 Surface temperature plots for a) 34 filament with packing fraction 0.417, b) 34 filament with packing fraction 0.475, c) 68 filament with packing fraction 0.441 and d) 68 filament with packing fraction 0.494

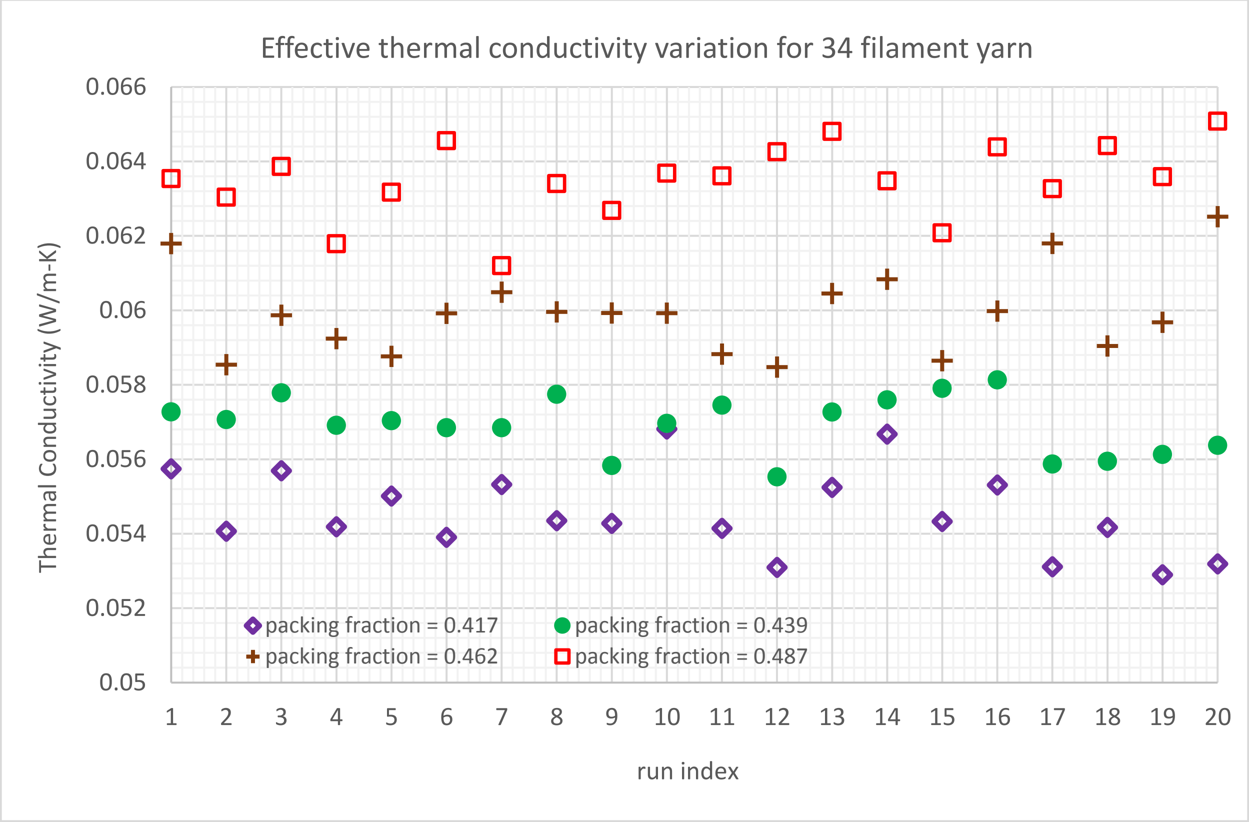

Figure 7 Effective thermal conductivity variation with run index for different porosities of 34 filament yarn

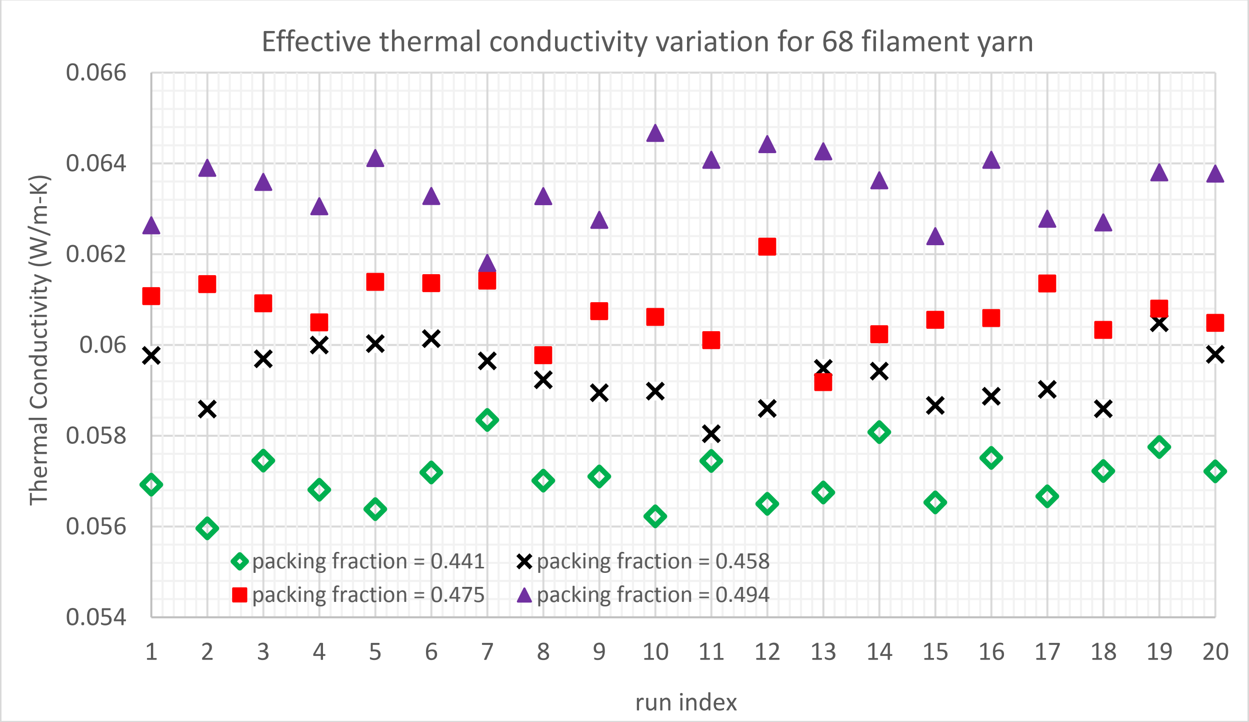

Figure 8 Effective thermal conductivity variation with run index for different porosities of 68 filament yarn

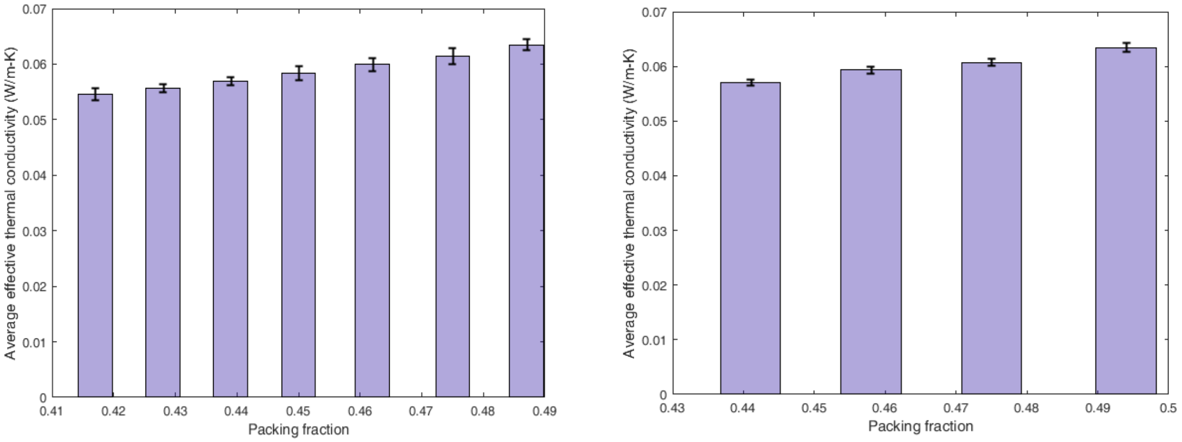

Figure 9 Variation of Average thermal conductivity for 20 random runs with packing fraction for 34 and 68 filament yarns

Conclusion

These simulation results reveal that at a fixed packing fraction, the thermal conductivity of the yarns can vary significantly. Furthermore, the packing fraction remains the dominant factor in determining the effective thermal conductivity, but the significant deviation at different packing arrangements also suggests that there are certain geometrical factors and arrangements that are important and can become significant when the microfiber cross sections are not symmetric in nature.

Acknowledgement

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