# Heat Transfer in Fibrous and Textile Materials: A Literature Review

Lukas Capek[1], Petr Henyš[1], and Felix Saucedo[2]

[1]Laboratory of Experimental and Computational Biomechanics
[2]Affiliation not available

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## Introduction

Heat conduction in heterogeneous media such as composite materials, porous media and fibrous materials have extensive industrial applications since in them there is usually a quite small spatial region, in which the physical properties change dramatically and the derivatives of physical quantities do not exist anymore. Fibrous materials have been used extensively because of their ease of fabrication, relatively low cost and superior mechanical and thermal properties. The most common applications include building insulations, heat exchangers, grain storage, energy conservation, drying technology, oil extraction, geothermal systems, nuclear waste disposal, space technology as well as functional clothing design in textile engineering **???**.

The clothing system is needed to protect the body against hostile climatic conditions and it plays a very important role in human thermal responses because it determines how much of the heat generated in the human body can be exchanged with the environment. With the development of new technology, it is becoming important to know how the human body will behave thermally under different environmental conditions with various clothing systems. Therefore, a lot of research has been done and is still going on to understand the phenomenon of steady state heat transfer in general and through textile and porous materials in particular. Thermal properties of textiles are sought in areas where thermal insulation is an important issue, especially in thermally hazardous conditions **??**.

The thermal behaviour of fibrous materials is indicated by its thermal conductivity, which depends on the physical structure of the material. For example, it strongly depends on porosity, fiber geometry, temperature range, fiber arrangement (isotropic or anisotropic) and the contact between fibers **?**. It was then found necessary to investigate the different kinds of heat transfer, and their importance to the total thermal conductivity of the material. There, different types of heat transfer are present: conduction by the solid material of the fibers, conduction by intervening air, radiation, and convection **?**. Compared to a material with closed pores, the gas in textile and fibrous material is not enclosed in defined pores. It is thus possible to experience a gas flow that influences the thermal behaviour of the material, and increases or decreases its effective thermal conductivity **?**.

In textile materials, the majority of textile fibers have certain degree of moisture absorption capability (called hygroscopicity). The moisture absorption influences the heat and moisture transfer processes and it implies a further computational effort since it requires to solve a coupled heat and mass transfer system **?**.

This systematic literature review employed the PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) approach **?**. Two databases (Web of Science and Scopus) were searched for relevant articles using the following keywords: (heat transfer) AND ((textile material) OR (fibrous material) OR (clothing)) AND ((analytical solution) OR (numerical solution) OR (theoretical solution)) AND (meshless

*). For each article, the reference lists and forward-citation reports from each database were consulted in order to identify additional relevant articles that were not found in the automatic search.

Therefore, the theoretical and numerical research on the thermal properties of textile materials can be categorized into the following categories:

1. Studies on heat transfer through textile and porous materials.
2. Studies on heat and mass transfer through textiles and fibrous materials.

Fig. 1 and Fig. 2 is show the number of articles published per year in the last two categories.

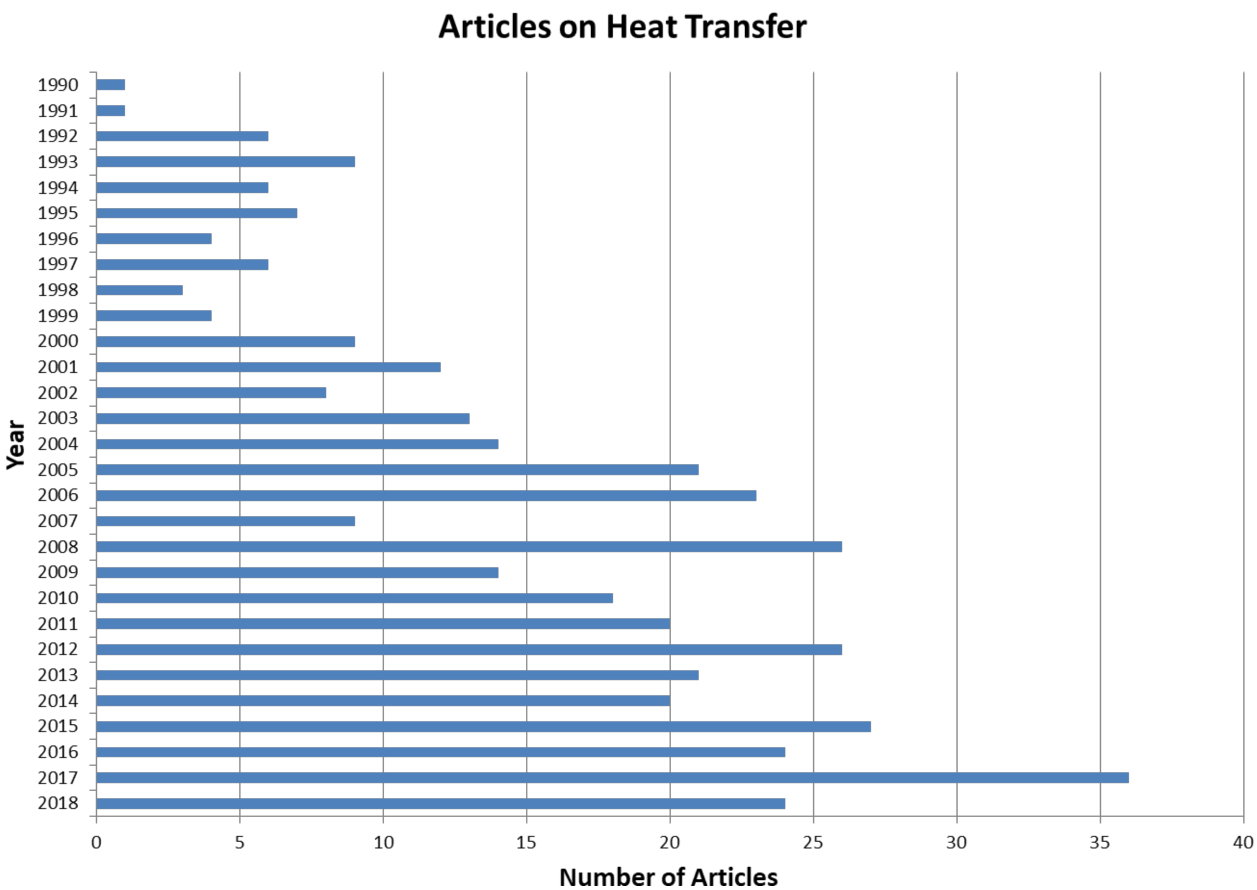


Figure 1: Number of articles on heat transfer per year

In the following lines, a literature review on the first category is given.

## Studies on heat transfer through textile and porous materials

C. G. Bankvall studied the mechanisms of heat transfer in fibrous insulations considering that there was no gas flow in the material which would give no convective heat transfer. He theoretically computed the mechanisms of heat transfer in fibrous materials and experimentally verified these calculations by measurements on a glass fiber insulation ?.

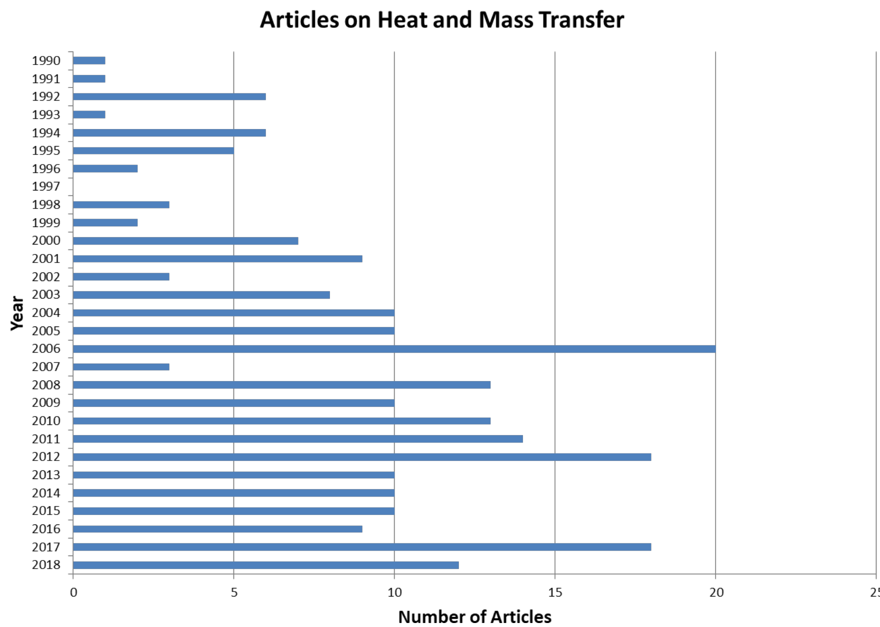


Figure 2: Number of articles on heat and mass transfer per year

M. I. Ismail et al. developed a mathematical model that represents the fabrics under normal conditions which facilitates the application of the heat transfer equations. With this model it is possible to compute the effective thermal conductivity of fibrous materials in a fabric form, yarn form, or even in fiber form **?**.

S. Y. Fu and Y. W. Mai studied the effects of the fiber length distribution and orientation distribution into the effective thermal conductivity of short-fiber-reinforced polymer composites. They observed that the thermal conductivity of the composite increases with mean fiber length but decreases with mean fiber orientation angle with respect to the measured direction **?**.

M. Wang et al. applied the Lattice Boltzmann Method for predicting the effective thermal conductivity of natural fibrous materials accurately, considering the multiphase conjugate heat transfer effect and a random generation-growth method for generating micro morphology of natural fibrous materials. They found that the fiber orientation angle limit produces anisotropic effective thermal conductivities and that a smaller orientation angle leads to a stronger anisotropy. The effective thermal conductivity of fibrous materials increases with the fiber length and approach a stable value when the fiber tends to be infinitely long. Finally, the effective thermal conductivity increases with the porosity of material at a linear rate and differs for different fiber location distribution functions **?**.

Y. Yamashita et al. derived structural models of yarns, plain weave fabrics and plain weave fabric/resin composites and theoretical formulas for the effective thermal conductivity for these structural models **?**.

V. K. Kothari and D. Bhattacharjee developed a mathematical model to predict the conductive and radiative heat transfer through fabrics and validated such model with thermal resistance values published in the literature. By using computational fluid dynamics they investigated the effects of convection on the total heat transfer of the fabric, considering natural and forced convection. They found that the mathematical model predcit very well in forced as well as natural convective modes **??**.

S. Cimilli et al. investigated the applicability of a finite element method (FEM) to textile problems. They analysed the heat transfer of plain knitted fabric and compared their numerical results with experimental ones. They showed that the FEM model developed for the heat transfer measurement including plain knitted cotton fabric produces very promising results and it has the potential to obtain effective heat conduction coefficients of fabrics from new fibers such as bamboo, soybean, chitosan, some of which are not available in the literature at present **?**.

I. Qashou et al. investigated the response of a fibrous material to the radiative heat transfer by solving the unsteady state heat transfer equation for the temperature and heat flux in and around the fibers that constitute a nonwoven fibrous material. Their numerical results were compared with experiment and good agreement was found **?**.

A. Das et al. developed a mathematical model for the prediction of heat transfer through multilayer clothing with air in between two successive layers of fabric in a multi layered clothing assembly by using the general equations of heat transfer through porous media. The model was validated with some experimental results which show well agreement **?**.

M. Matusiak proposed a model of thermal resistance of woven fabrics and it was verified experimentally on the basis of results obtained for plain weave fabrics as well as for fabrics of non-plain weave **?**.

H. Hasani et al. investigated the applicability of the finite element method (FEM) to analyse the heat transfer behaviour of plain interlock weft knitted fabrics. They developed an interlock weft knitted fabric model based on FEM and studied the heat transfer behaviour of this fabrics. Their steady heat transfer analysis considered a fixed temperature on one side of the fabric and placed it in air which has temperature less than the applied temperature which allows the heat to flow, considering that the heat transfer is by conduction and convection. Nonetheless, they ignored the interaction between the air and fabric considering that fabric space was not removed from the air domain **?**.

M. O. R. Siddiqui and D. Sun developed a finite element model to predict the effective thermal conductivity and thermal resistance of the woven fabrics. Their model was validated by experimental results of effective thermal conductivity and thermal resistance of the fabric and the model was further analysed by the use of temperature dependent thermal conductivities of the fiber and different fiber volume fraction of the fabric **?**.

J. Fan et al. evaluated the steady-state heat transfer performance of three-layer branching-structured biomimic woven fabric by applying temperature-specified boundary condition with a finite element method. They compared their numerical thermal conductivity with experimental results, where a good agreement was found **?**.

N. Nouri and A. Martin proposed a a three-dimensional model to calculate the effective radiative conductivity of anisotropic fibrous materials considering that the fibers are in a cylindrical shape. They found that the computed conductivity depends of both temperature and the orientation of the fibers **?**.

A. K. Puszkarz et al. modelled the heat transfer phenomena through a 3D weft knitted fabric by means of the finite volume method considering a heat flow under steady conditions, considering the yarns as a solid continuous structure in a form of monofilaments characterized by isotropic thermal properties. They proposed a three-dimensional approach in SolidWorks software for modelling knitted fabric structures for future analysis of physical properties and thermal phenomena **?**.

M. O. R. Siddiqui and D. Sun developed finite element models to predict the thermal conductivity of plain weft knitted fabrics considering different fiber orientation and anisotropy of fiber. Their model was validated by experimental results obtained from an in-house developed device **?**.

Z. Zheng et al. studied the impact of the weave structure, warp density and yarn fineness on the thermal insulation of glass fiber fabrics by using numerical simulation. They validated the simulation results with some experiments and found a good agreement. They found that an increase in the warp density leads to a significant decrease in heat transfer performance **?**.

M. O. R. Siddiqui and D. Sun proposed a finite element model of plain weft knitted fabric by considering actual environment of experiment using an hybrid finite element and finite volume method by applying actual boundary conditions, and evaluated its thermal properties. Their numerical results were compared with experimental results, and they found that they were highly correlated. Moreover, they used the validated models to evaluate the velocity and temperature profile of air at out-plane created over the knitted fabric surface **?**.

Coming up next, a literature review on the second category is given.

## Studies on heat and mass transfer through textiles and fibrous materials

The first model that describes the mechanism of transient diffusion of heat and moisture transfer into an assembly of hygroscopic textile materials was introduced and analysed by P. S. H. Henry **??**. He developed a set of two differential coupled governing equations for the mass and heat transfer in a small flat piece of clothing material. His analysis was based on a simplified analytical solution **?**.

Y. Ogniewicz and C. L. Tien studied the condensation in porous insulation considering a steady-state one-dimensional formulation. In their model they assumed that heat is transported by conduction and convection along with phase change. They found that the effect of condensation, due to release of latent heat, is significant on the overall thermal performance **?**.

S. Motakef and M. A. El-Masri analytically investigated simultaneous heat and mass transfer with phase change in a porous slab considering by first time a second spatially steady regime during which the temperature, vapour concentration and liquid-content profiles are time invariant **?**.

A. P. Shapiro and S. Motakef analytically investigated simultaneous unsteady one-dimensional heat and mass transfer with phase change in a porous slab and compared the analytical results with experimental ones. They found that for a large class of problems the rate of motion of the wet zone can be decoupled from the transient change in the temperature and species fields, and the unsteady process can be reduced to that of quasi-steady fields in time dependant domains. This analysis is only valid when the time scale for the motion of the dry-wet boundary in porous media is much larger than the thermal diffusion time scale **?**.

B. Farnworth presented the first dynamic simplified model of coupled heat and moisture transfer with sorption and condensation for multi-layered clothing. In this model he considered the heat transfer by conduction and radiation, and the moisture by diffusion. He found that in both phases, the condensation, absorption, or evaporation substantially influences the heat transfer and that in the case of clothing previously wetted by external means, the heat transfer continuously changes as the clothing dries **?**.

K. Vafai and S. Sarkar studied the moisture accumulation and the increase of the effective thermal conductivity of a fibrous insulation slab as an effect of moisture transfer. They modelled the transient heat and moisture transfer with condensation and variable properties, in a porous slab with impermeable, adiabatic horizontal boundaries and permeable vertical boundaries. There, they numerically analysed the effects of boundary conditions, the Peclet and Lewis numbers on the condensation process **?**.

Later K. Vafai and H. C. Tien extended the previous results to two-dimensional heat and mass transfer with phase change in porous materials considering a system of two-dimensional transient governing equations for the multiphase transfer process in the porous matrix. They considered different numerical schemes versions in order to examine the stability and accuracy. Their model allows a full simulation without any significant simplifications **?**.

Y. X. Tao et al. studied the moisture and frost accumulation in a glass-fiber insulation slab with the Vafai and Sarker's model **?** considering temperatures below the triple point of water. They found that the motion of the frozen boundary is primarily governed by thermal diffusion **?**.

K. Murata presented an experimental and analytical study of heat and moisture transfer with condensation in a fibrous insulation slab considering a model in which the condensation occurs on a bounded cold surface and in the interior of the fibrous insulation, and considering by first time that the condensate falls away under gravity action **?**.

P. W. Gibson and M. Charmchi developed a set of partial differential equations describing time-dependent heat and mass transfer through porous hygroscopic materials and a numerical code to solve this set of non-linear coupled equations. They conduct simulations and experimental testings of steady diffusion-convection processes in textiles, where pressure drop and relative humidity varied across the textile material **?**.

D. A. S. Rees and I. Pop studied the variable permeability effects on the flow and heat transfer in a porous medium, considering that it is bounded by an impermeable surface **?**.

K. Ghali et al. experimentally investigated and theoretically modelled the ventilation effect on heat and mass transfer through textile materials as a function of the velocity of penetrating air without assuming local thermal equilibrium in the fiber **?**.

Y. Li and Q. Zhu proposed a mathematical model for simulating flow fields in porous textiles with consideration of gravity. Their model assumes that the liquid water moves in the composite network of capillaries of the porous textile by capillary action and gravitational force, including the phase change effects **?**.

J. Fan and X. Y. Cheng developed a theoretical finite-difference model of coupled heat and moisture transfer within clothing assemblies of fibrous materials with moisture absorption, phase change, and mobile condensates. They found good agreement between the results of their model and experimental results. Further, their simulation results show that for clothing consisting of fibrous battings sandwiched by two layers of thin fabrics, inner fibrous battings with a higher fiber content, finer fibers, greater fiber emissivity, higher air permeability, a lower disperse coefficient of surface free water, and a lower moisture absorption rate produces less condensation and moisture absorption, which is beneficial to thermal comfort during and after excising in cold weather conditions. Therefore, their theoretical analysis could be used to understand the mechanism of condensation within clothing **?**.

Y. Li and J. Fan numerically studied the transient heat and moisture transfer in clothing insulation made of fibrous battings and covering fabrics by using the finite volume method (FVM). There, they considered an upstream scheme for the moisture bulk flow and the effect of condensate on the permeability of the fibrous batting, which improves the accuracy of the numerical solution. With this approach, they investigated the effects of various clothing parameters on the condensation and moisture absorption within clothing. They found that for clothing consisting of fibrous batting sandwiched by two layers of thin fabrics, inner fibrous batting having higher fiber content, finer fiber, greater fiber emissivity, higher air permeability, lower disperse coefficient of surface free water, and lower moisture absorption rate will cause less condensation and moisture absorption, which is beneficial for thermal comfort during and after exercising in cold weather conditions **?**.

C. Ye et al. studied heat and moisture transfer in clothing assemblies, based on a multi-component and multi-phase flow model which includes heat/moisture convection and conduction/diffusion as well as phase change. They proposed a splitting semi-implicit finite volume method for solving a set of nonlinear convection-diffusion-reaction equations, in which the calculation of liquid water content absorbed by fiber is decoupled from the rest of the computation. They compared several practical cases of clothing assemblies with experimental data **?**.

M. Aihua and L. Yi developed a measurable-parameterized numerical model to simulate the transient heat transfer coupled with multidimensional liquid diffusion in porous textiles.There, they employed a model of human body to simulate the thermo-regulatory behaviours and the thermal responses between the textiles and body skin, which are considered through the boundary conditions for the accuracy of realistic wearing situations. The results from this model were validated with experimental data where good acuracy was found **?**.

J. Fan et al. presented an improved transient FVM model, integrating conductive and radiative heat transfer, moisture diffusion, moisture bulk flow, moisture sorption and desorption as well as phase change, which was validated by subzero experiments **?**.

Q. Zhang and W. Sun numerically studied the heat and moisture transfer in clothing assemblies described by a multi-component and multiphase air–vapor–heat flow with a moving interface. For their solutions, they applied a splitting semi-implicit finite volume method for the system of nonlinear parabolic equations and an implicit Euler scheme for the interface equation **?**.

X. J. Ran et al. proposed a 3D mathematical model to measure the coupled heat and mass transfer in woven fibrous materials considering its geometrical characters. They used the finite volume method to solve governing equations and the TDMA algorithm to solve the resulting discretized equations. They developed too a high order and absolutely stable difference scheme for water vapour diffusing in fiber. The model was validates with some experimental measurements where good agreement is observed **?**.

# Conclusions

Accurate and efficient modelling of the temperature field is key to the analysis and design of textile materials. Several numerical schemes have been developed to obtain approximate solutions of simplified models of heat and mass transfer in fibrous materials. Classical numerical methods such as the finite volume method (FVM) and finite element method (FEM) are widely used. These have been used to derive numerical methods such as the boundary element method (BEM) to solve the heat conduction problem in non-homogeneous and functionally gradient materials with high accuracy. Nevertheless, these traditional methods have some difficulties in treating this kind of problems with moving boundary problems which could be solved with meshing and re-meshing approaches. A large family of meshless methods has been proposed in the last decade to deal with this kind of problems without requiring and element mesh which is the main source of the constraints found in these traditional mesh-based methods. Therefore, the study and application of meshless methods to analyse heat and mass transfer in textile and fibrous materials depicts a rich source of research opportunities.