STSM report COST FP1404

Katrin Nele Mäger, From Tallinn University of Technology to Technical University of Munich (16.01.-26.02.2017)

- **The purpose** of this STSM was to develop the procedure of adding new materials to the improved component additive method. The focus was on studying the behaviour of bio-based fibrous insulation materials in the standard fire scenario and to develop the thermal properties to describe these materials with enough accuracy in thermal simulations. The greater outcome was developing the design equations for cellulose and/or wood fibre insulations.
- **In short** the work firstly comprised of an extensive online literature survey. Different thermal simulation software were compared to ensure correct simulation results. Some possible solutions to account for the fall-off of insulation in analytical simulations were discussed. Preliminary product-specific thermal properties and equations were developed.
- The **main outcomes** are a collaborative article for Fire Safety Journal and comparison of thermal behaviour of analogous materials present in different areas of the European market
- **Future collaboration** with the host institute is already planned to further study the influence of using different simulation software and the limits to mesh size and time step lengths within numerical investigations of separating timber frame structures. Furthermore, a collaborative study of the thermal properties of cellulose and wood fibre insulations is ongoing.
- The results of this STSM could form a part of the background for the new Eurocode, with respect to the possibility to include cellulose and wood fibre insulations in the improved component additive.
- Confirmation by the host institution of the successful execution of the STSM is attached (annex 1)

Fire test of unprotected loose fill cellulose fibre insulation fixed with chicken net and steel bars

Annex 1 – Confirmation by Host Institution

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COST FP 1404

Chair: Dipl. -Ing. Joachim Schmid
STSM Manager: Dr. Alar Just

Munich, 24. March 2017

Confirmation of performed STSM - Katrin Nele Mäger

Dear Mr. Schmid and Dear Mr. Just,

I am pleased to confirm that Katrin Nele Mäger, researcher at Tallinn University of Technology, Department of Civil Engineering and Architecture, Estonia successfully completed her STSM at the Technical University of Munich, Chair of Timber Structures and Building Construction, Germany, between the 16th of January until the 26th of February.

The purpose of the STSM was to improve a procedure of adding new materials to the improved component additive method. The focus was on studying the behaviour of bio-based fibrous insulation materials, such as wood fibre insulation, in the standard fire scenario and to develop the thermal properties to describe these materials with enough accuracy in thermal simulations.

I am therefore very happy to confirm that the STSM was completed as planned and the objectives reached.

Please do not hesitate to contact me about further information of this STSM.

Kind Regards

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Annex 2 – Scientific Report

Fire safe use of bio-based building products

Development of a procedure for the determination of design equations for the improved component additive method

Scientific report of STSM at Technical University of Munich

16.01-26.02.2017

Author:

Katrin Nele Mäger, Tallinn University of Technology

Table of Contents

Introduction

Bio-based insulation materials have been on the market for years. Their behaviour in fire is somewhat of an issue of the subjective feeling prevalent in the general public. Bio-based materials can give equal results to conventional materials when structures are carefully designed. The work conducted during this STSM should give valuable input to the expansion of the current calculation methods for evaluating the separating function of structures.

The focus of this work was to study cellulose and wood fibre insulations in fire and to determine their thermal properties at elevated temperatures. The importance of this collaboration was also to investigate the different products on the market as my previous work includes some work on a Nordic cellulose fibre insulation product.

As different simulation software is used in the host organisation, an extensive study of the different approaches was also conducted.

Work is continuing on determining the limitations of the simulation software in terms of accuracy of results depending on the mesh size and time steps. Another future goal is to obtain the thermal properties of the materials tested at TUM and compare the results to hopefully derive more general effective properties of cellulose and wood fibre insulations.

Overview of performed work

The main aim of this STSM was to study the behaviour of cellulose and wood-based thermal insulation materials in the standard fire scenario. The focus was on the separating function of timber structures insulated with the investigated materials.

Firstly, a literature survey was conducted to determine results of previous studies. The data about the investigated materials is rather scarce. This makes the results of this STSM and the connected projects all the more important.

The literature survey was broadened to include other common materials as well. The results obtained were quite varied which shows that the materials present on the market today differ greatly even if they are in compliance with the same product standards. The aim of the literature survey was to obtain thermal property data that would serve as the basis for determining the scope of the thermal properties and therefore stand as a means of evaluating the effective thermal properties obtained by iterative backwards calculation.

The reaction mechanics of cellulose and wood were studied. The issue is with the generalisation made during the development of thermal simulation software that heat inside materials is transferred only by conduction. In fibrous insulation materials solid conduction makes up the minority of the total heat transfer and gas conduction and radiative heat transfer ways are more prevalent (see Figure 20).

In addition, the limitations of thermal simulation software were investigated. In my work I use SAFIR v2014a1 software for the thermal simulations. In TUM Ansys is used. One area of investigation was to compare the results of these software and to determine the differences in approach. Two types of Ansys were used, the Ansys Workbench (Version 18) and the Ansys APDL input. One realisation was that Safir uses the enthalpy model for heat transfer analysis, as when comparing to Ansys workbench, the time steps were radically different.

In my previous work I have developed the effective thermal properties for one loose fill cellulose fibre insulation material. As TUM has performed fire tests on other cellulose and wood fibre insulation products, a comparison of the results was possible.

An important outcome of the STSM would be the results of the discussion regarding the fall-off or fastening of insulations. For material investigation purposes a special fastening system for the loose fill insulation was developed. That, however, is not feasible to be used in real buildings due to relative complicity and time-consuming installation. Hence, the performance of the material in real building structures would be drastically different than in the performed fire tests. The fastening and therefore fall-off of insulation materials could be considered in a different term in the actual calculations.

This work was focused on the separating function and providing the input for developing the equations for the improved component additive method. Load-bearing function and the protection to timber elements offered by the insulation materials must be investigated separately. Such work is being carried out by Tiso and Just [1].

Results and discussions

Literature survey of thermal properties

Timber structures are usually comprised of combinations of different materials. The most common material groups have been implemented to the improved component additive method by Schleifer [2]. With the development of new bio-based building materials, the method needs to be further expanded.

The first goal was to find thermal properties determined by material testing from online sources. This proved to be unfruitful as very little information has been published regarding bio-based insulation materials. For wood-based boards and inorganic boards data can be found pretty easily but is very dependent on the market where the products come from.

Regarding other materials commonly used in timber structures and especially timber frame assemblies, the results of the literature study were more successful. The interesting aspect was that very different values for the thermal properties were obtained.

The results are presented in the following graphs. [3] [4] [5] [6] [7] [8] [9] [10]

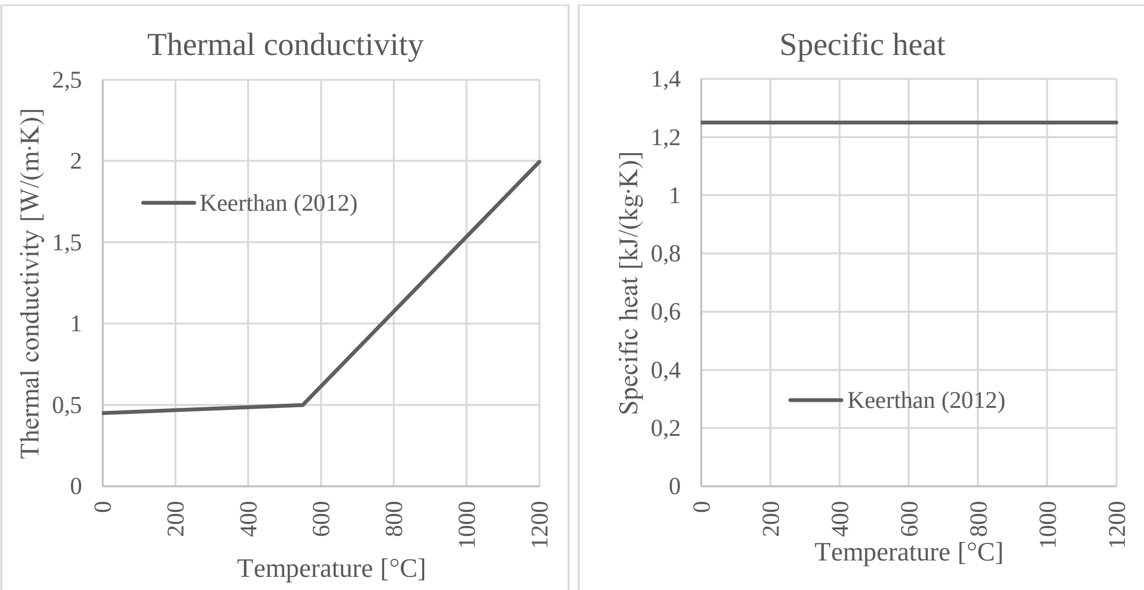

Figure 1: Thermal properties of cellulose fiber insulation from literature

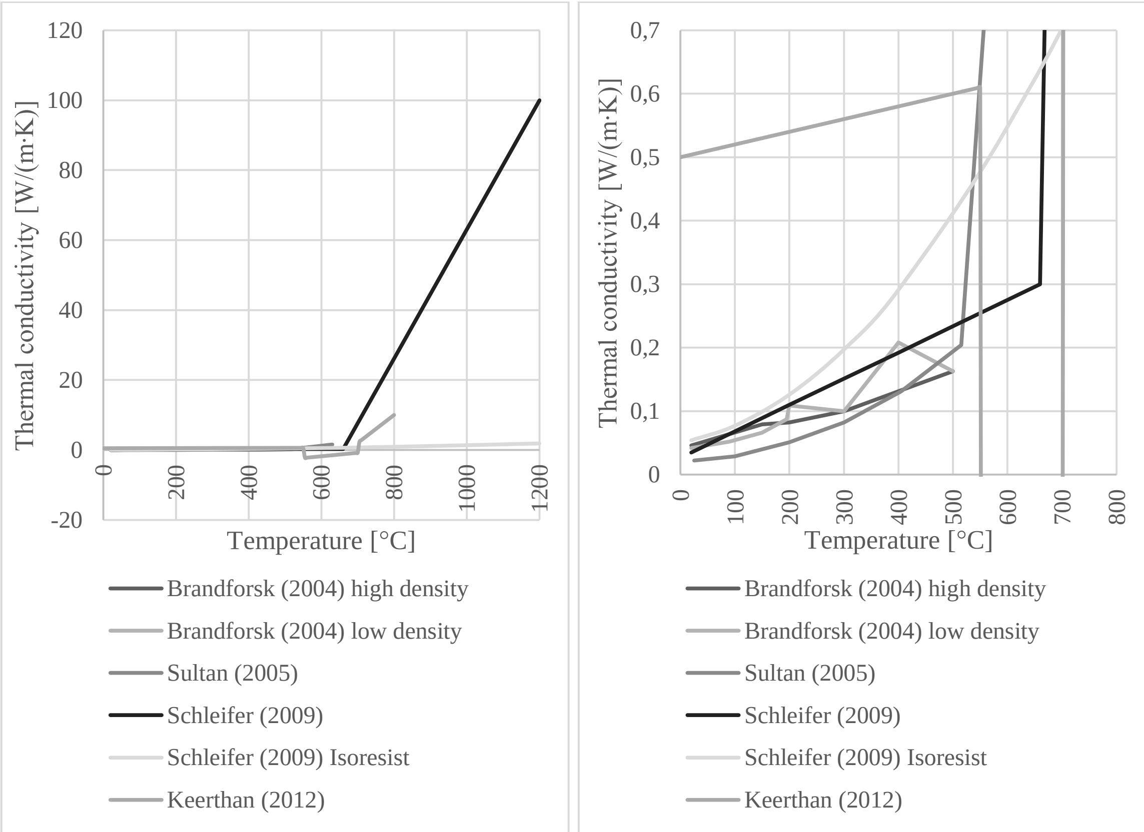

Figure 2: Thermal conductivities of glass wool insulation from literature (full graph on the left, fragment on right)

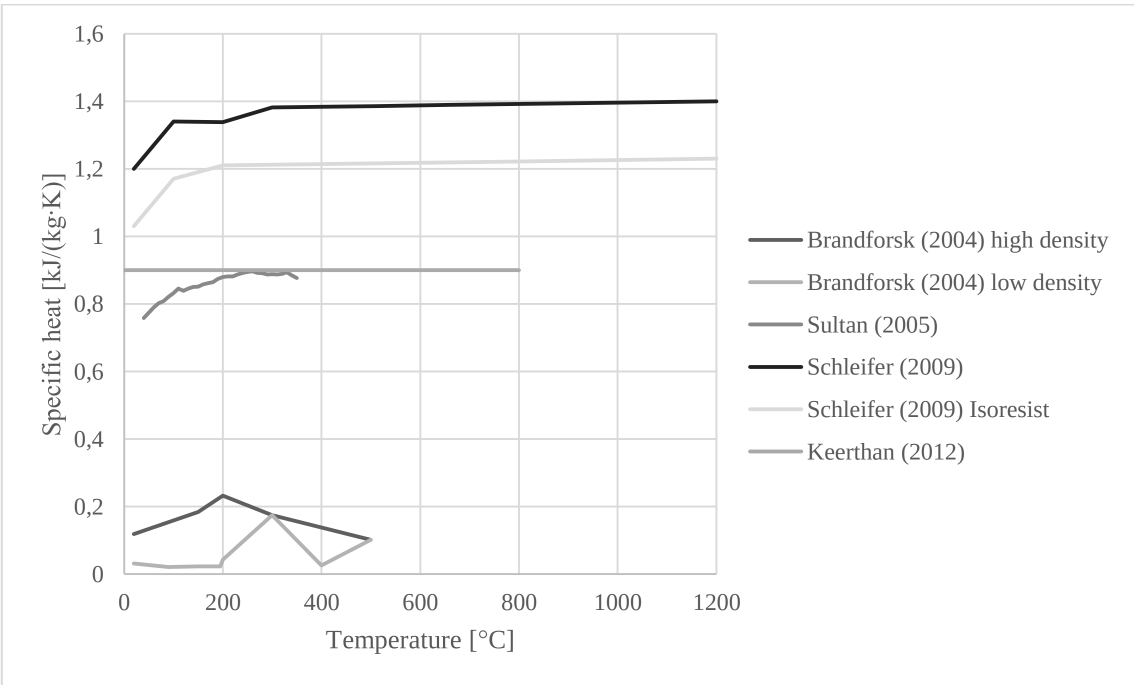

Figure 3: Specific heat values of glass wool insulation from literature

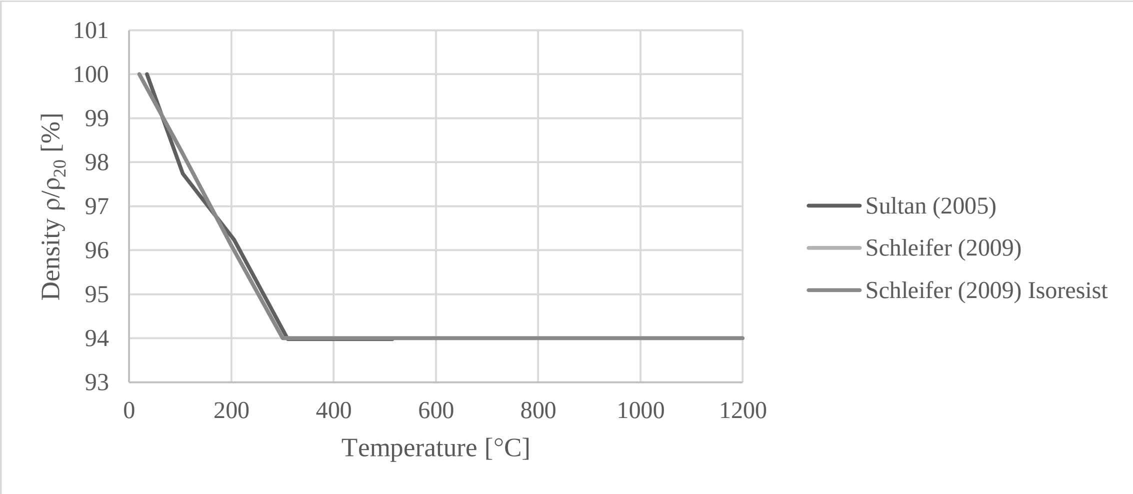

Figure 4: Change in density ratio (ρ_{fi}/ρ_{20}) of glass wool insulation from literature

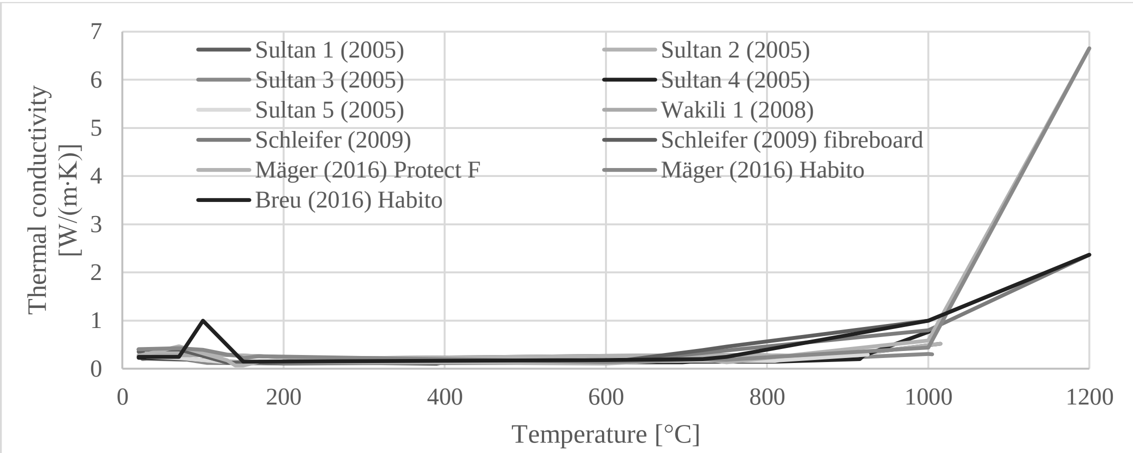

Figure 5: Thermal conductivity of gypsum plasterboards and gypsum fibreboards from literature

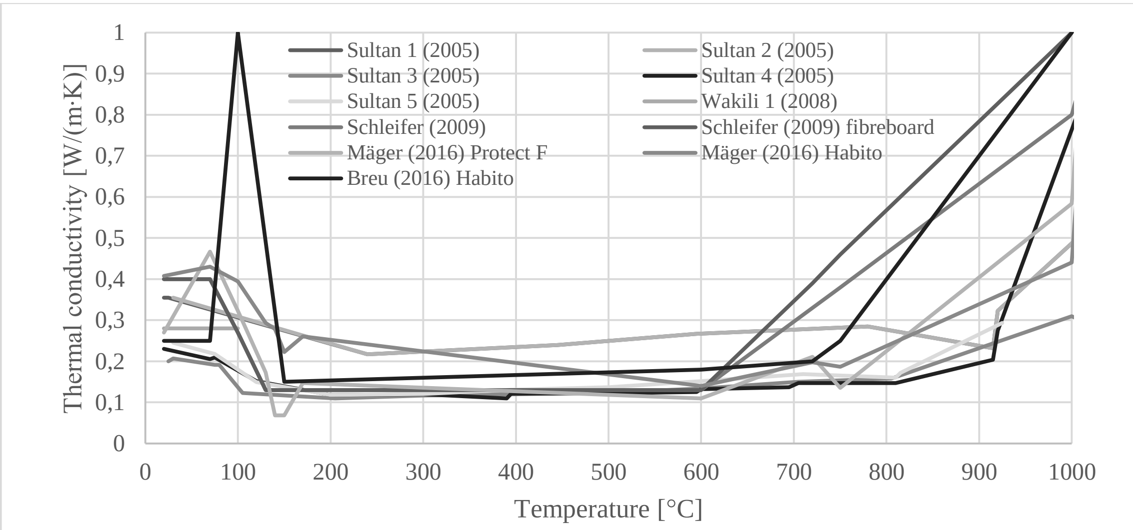

Figure 6: Enlargement of Figure 5

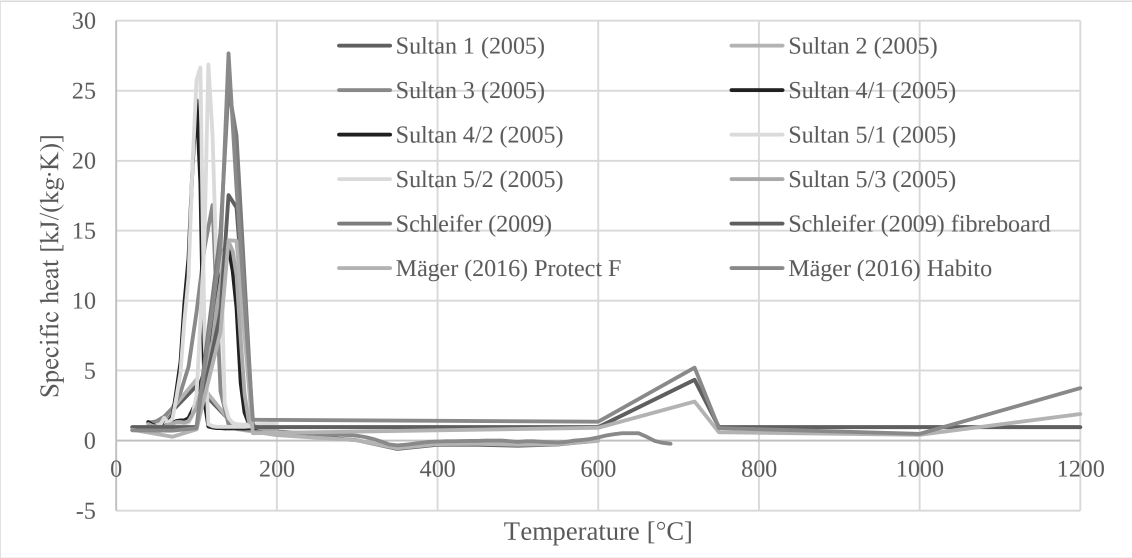

Figure 7: Specific heat of gypsum plasterboards and gypsum fibreboards according to literature

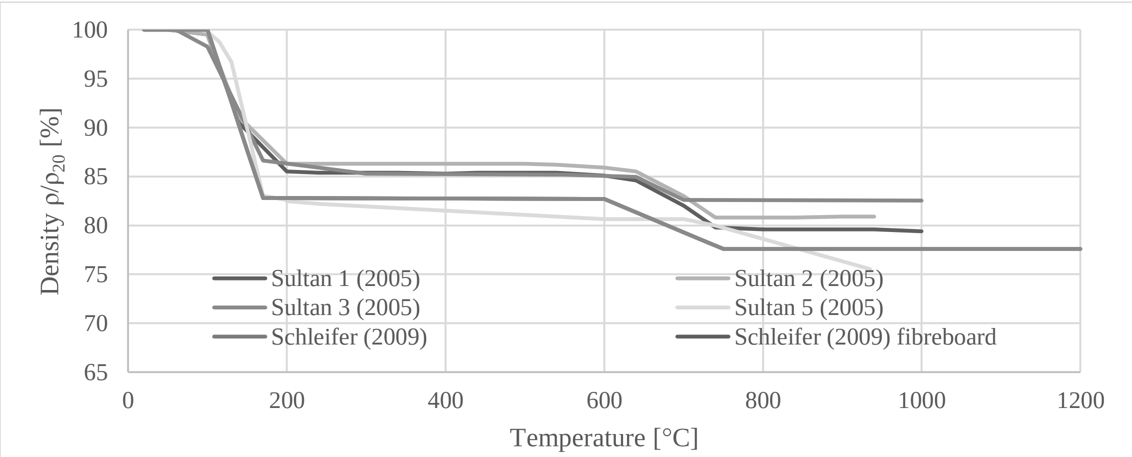

Figure 8: Density ratio (ρ_{fi}/ρ_{20}) of gypsum plasterboards and gypsum fibreboards according to literature

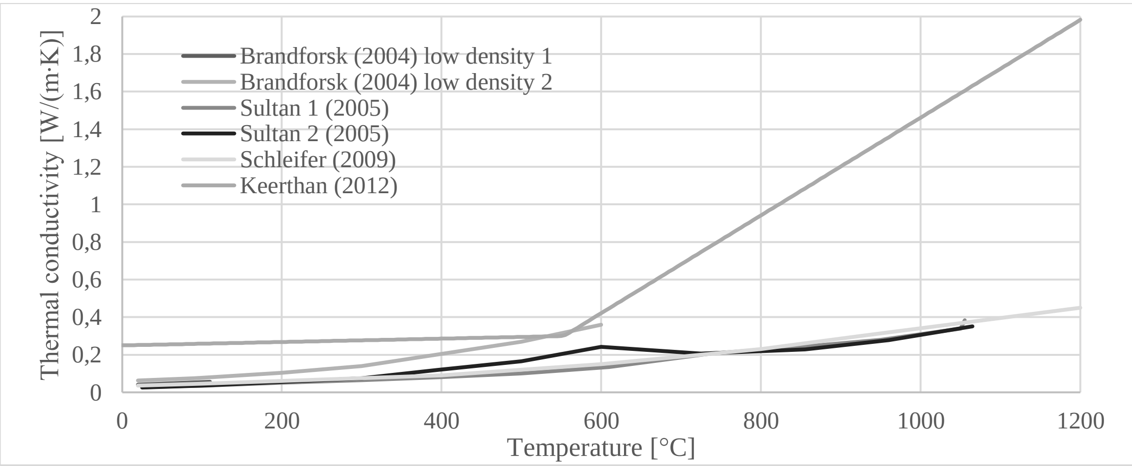

Figure 9: Thermal conductivity of stone wool insulation according to literature

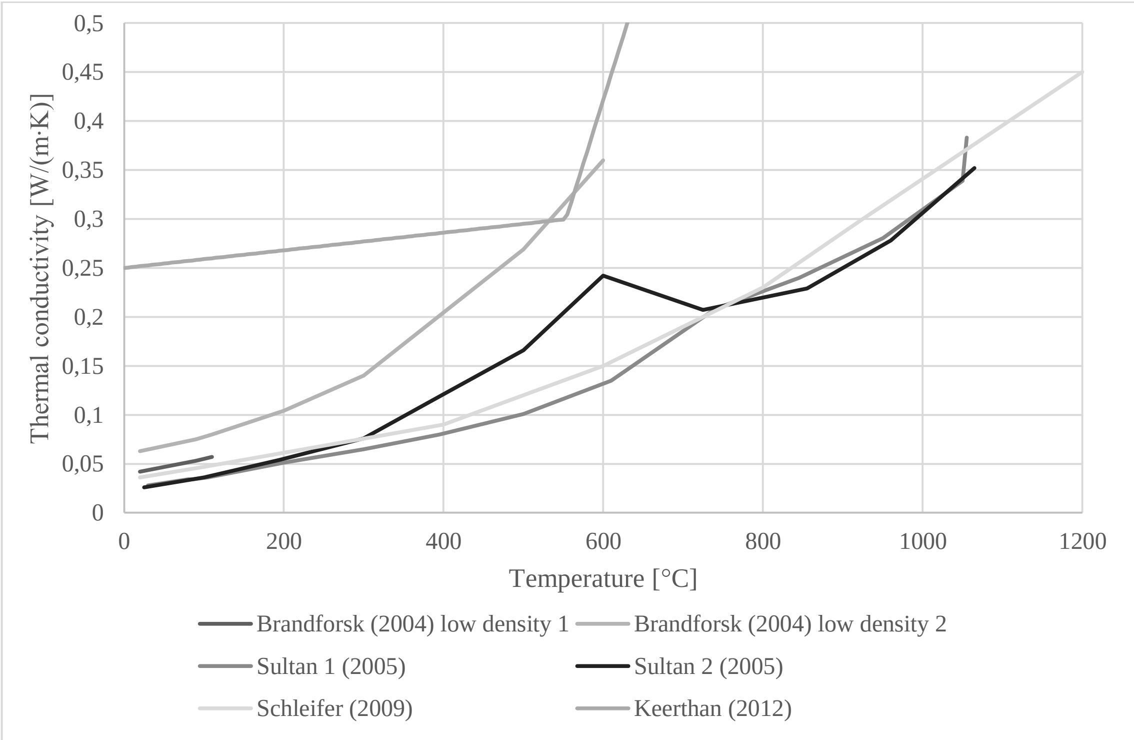

Figure 10: Enlargement of Figure 9

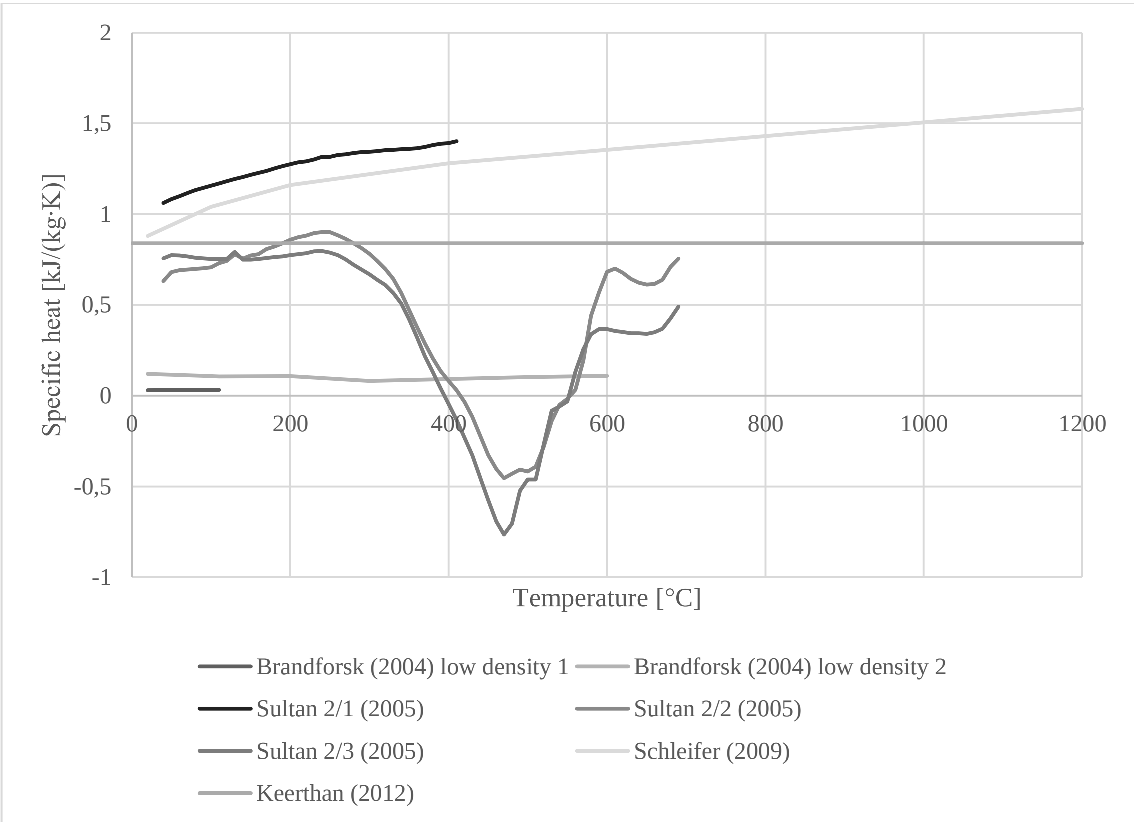

Figure 11: Specific heat of stone wool insulation according to literature

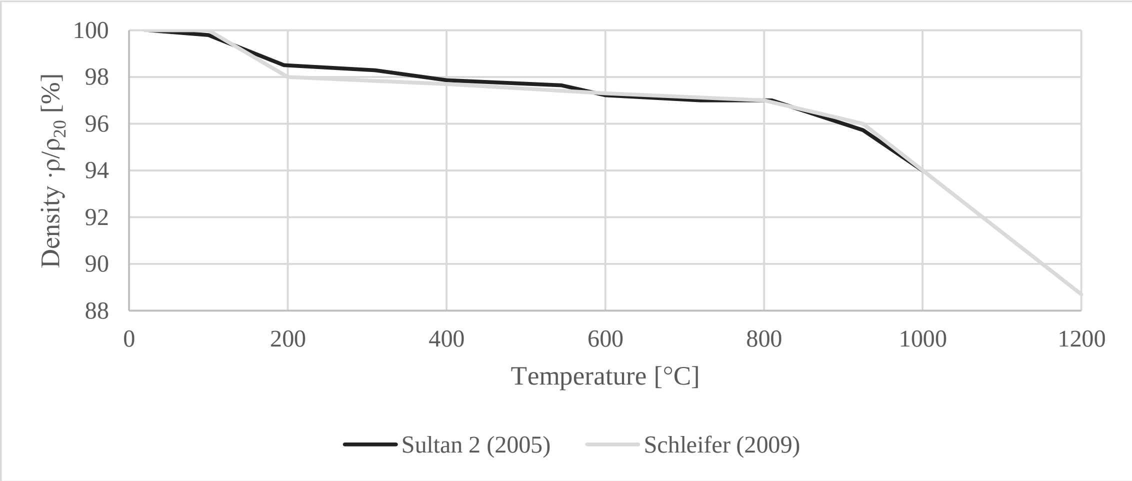

Figure 12: Density ratio (ρ_{fi}/ρ_{20}) of stone wool insulation according to literature

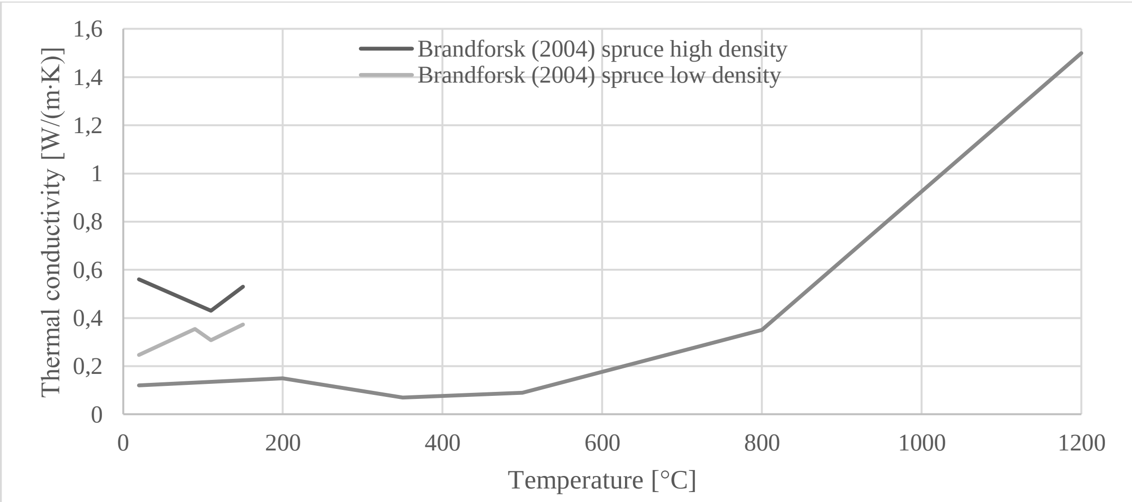

Figure 13: Thermal conductivity of timber according to literature

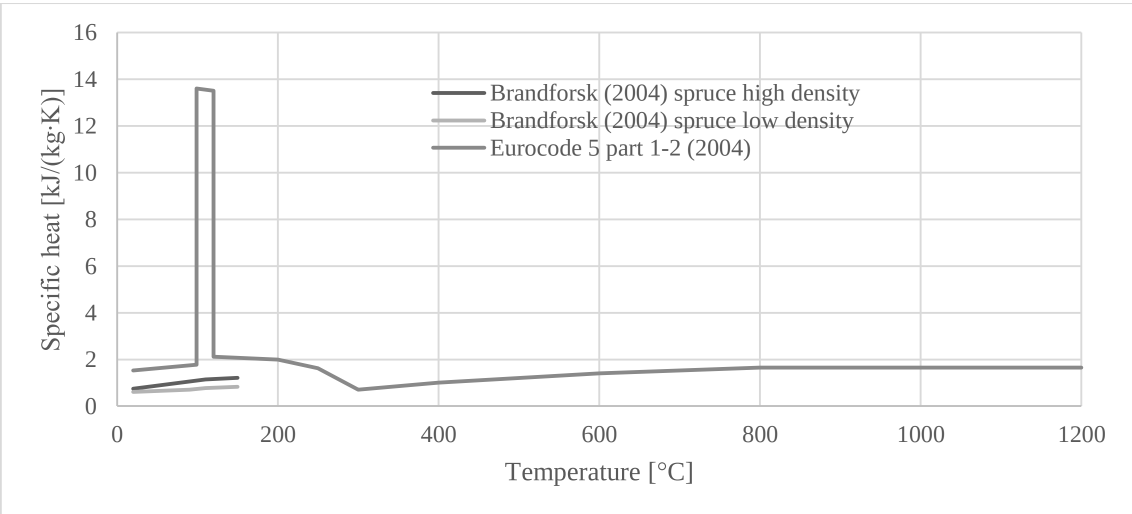

Figure 14: Specific heat of timber according to literature

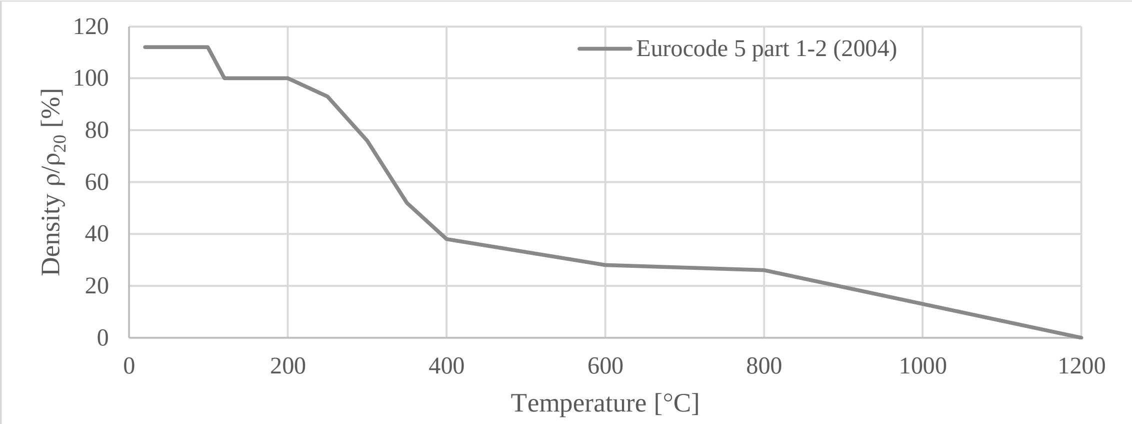

Figure 15: Density ratio (ρ_{fi}/ρ_{20}) of timber according to literature

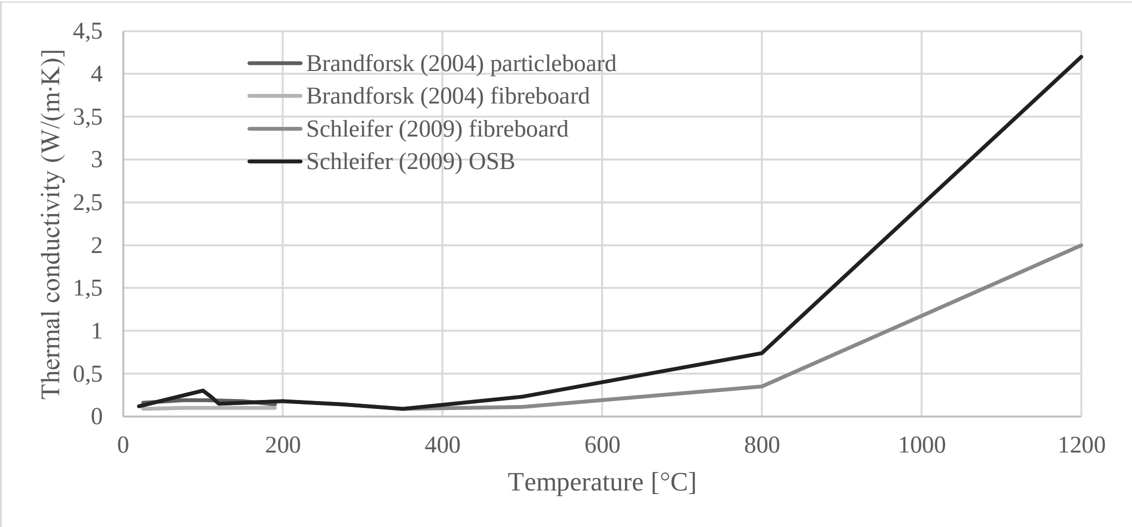

Figure 16: Thermal conductivity of wood-based boards according to literature

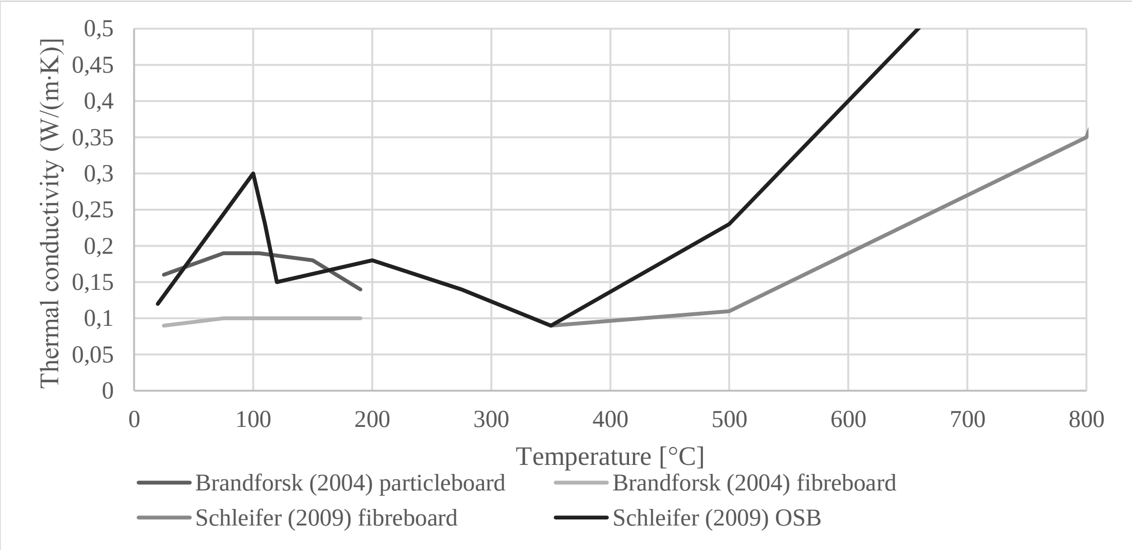

Figure 17: Enlargement of Figure 16

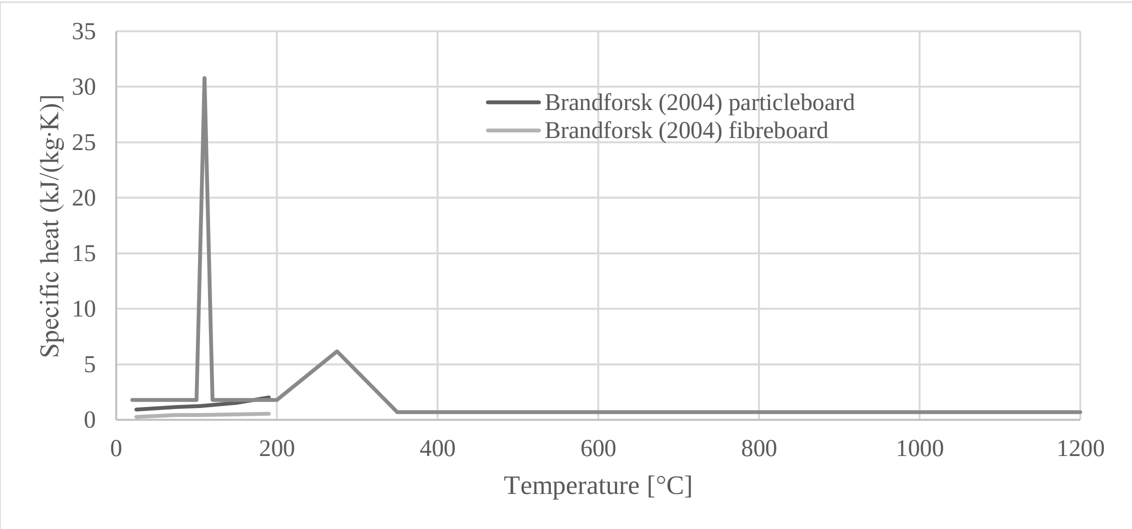

Figure 18: Specific heat of wood-based boards according to literature

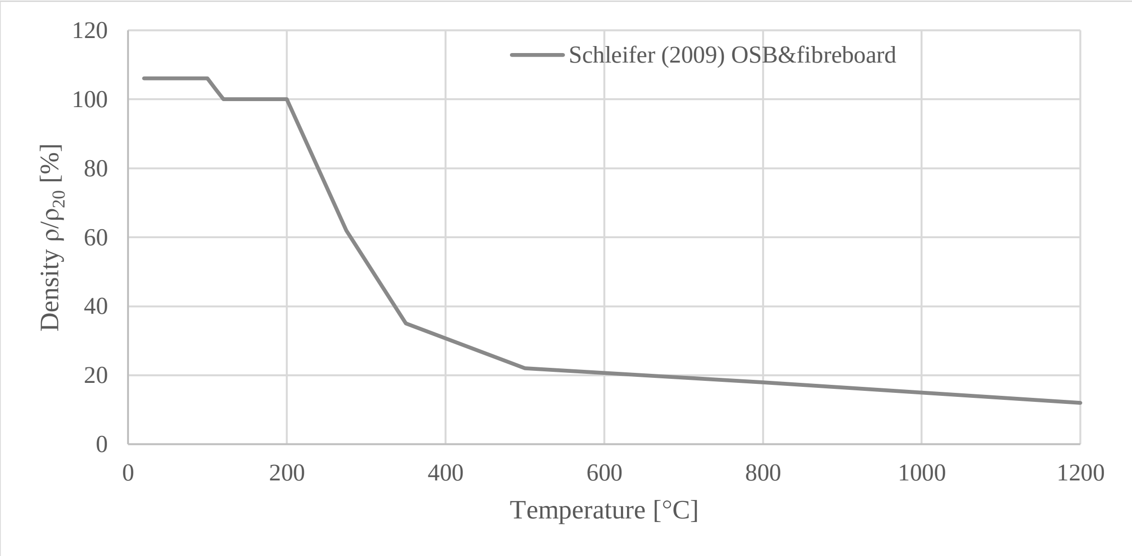

Figure 19: Density ratio (ρ_{fi}/ρ_{20}) of wood-based boards according to literature

Fibrous and bio-based insulation materials at elevated temperatures

The assumption in the heat transfer simulation software used for this study is that the simulated materials are made up of solid elements where thermal energy is transferred via solid conduction. In fibrous non-homogenous materials, this is a gross simplification and can be quite inaccurate.

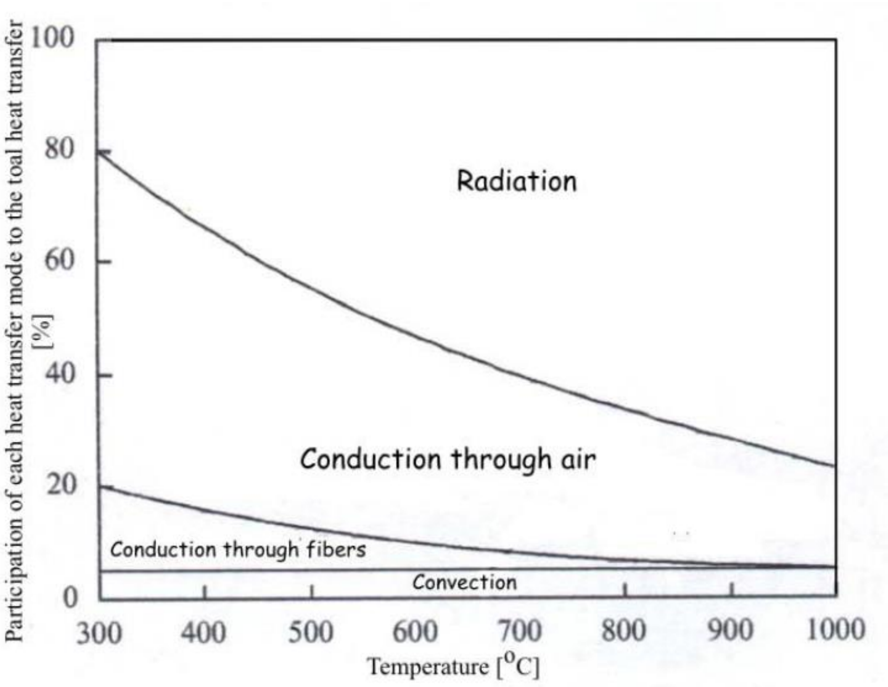

Figure 20: Heat transfer mechanisms in fibrous insulation materials according to [11]

Fibrous insulation materials transfer heat mostly via gas (air) conduction and radiation, the latter of which occurs on the surface of the solid fibres both from the air into the fibres and vice versa (see Figure 20). The modelling of such heat transfer is difficult to say the least, but some calculation models exist and have been used successfully [11] [12].

Another issue with low-density fibrous materials, especially with bio-based kinds, is the consideration of moisture movement in the material layer and the whole structure. The condensation and re-condensation of free water are phenomena that have been observed in fire tests but cannot be directly considered in the thermal simulations [13].

The previous shortcomings in the thermal simulation software leave two options. Firstly the rough engineering approach would be to generalise these phenomena by modifying the thermal properties. The other possibility would be to combine another calculation approach with the currently used conduction model and thereby carry out simulations which more accurately represent the actual fibrous material.

The first approach is more feasible in the current time and is probably accurate enough if appropriate caution is taken in the process of determining the thermal properties. In the current study a backwards calculation from fire test results was used (described in more detail in the next subchapter).

Thermal properties

Another obstacle in the thermal simulations is the physical changes of bio-based insulation materials at elevated temperatures. Cellulose and wood fibre insulation materials behave similarly to timber in fire by charring. The volume of the char layer is smaller than that of unheated material, therefore the charred material contracts and cracks. This creates unpredictable faults where heat transfer is significantly easier.

The charring temperatures of different components of wood (hemicellulose, cellulose and lignin) happen at different temperatures. This may be further altered by the use of flame retardant additives which are often used in bio-based insulation materials. [14]

Bio-based building materials can act as fuel in the fire scenario with further exothermal reaction at exposed surface which is a phenomenon completely ignored in thermal simulations. For thermal simulations this creates many problems which must be compensated also with proper modification of thermal properties.

Different approaches have been used to determine the thermal properties of building materials which yield appropriate results when compared to test data. One possibility is to manually change the input properties [9] to get simulation results which correlate with test data. Another possibility is to conduct essentially a backwards calculation and iteratively shift the simulation curve closer to the test results. The latter technique is used in this case.

The MATLAB code written as part of my master's thesis [8] was used to calibrate a cellulose fibre insulation material in loose fill type. The work started before the STSM but was finalised at TUM. The results of the calibration (Figures 20 to 21) were slightly worrying as some values of the properties were unrealistic and the peaks in the calibrated curves seemed to not correlate with actual reactions in the material.

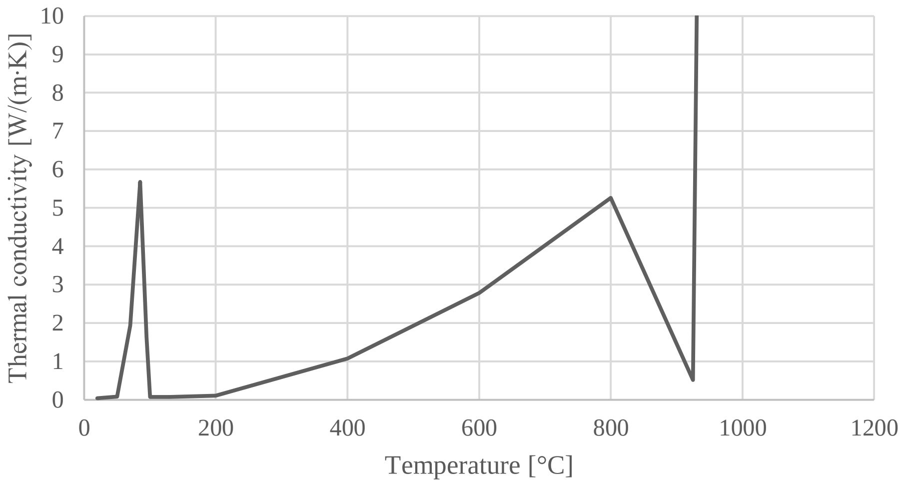

Figure 21: Thermal conductivity of a loose fill cellulose fibre insulation

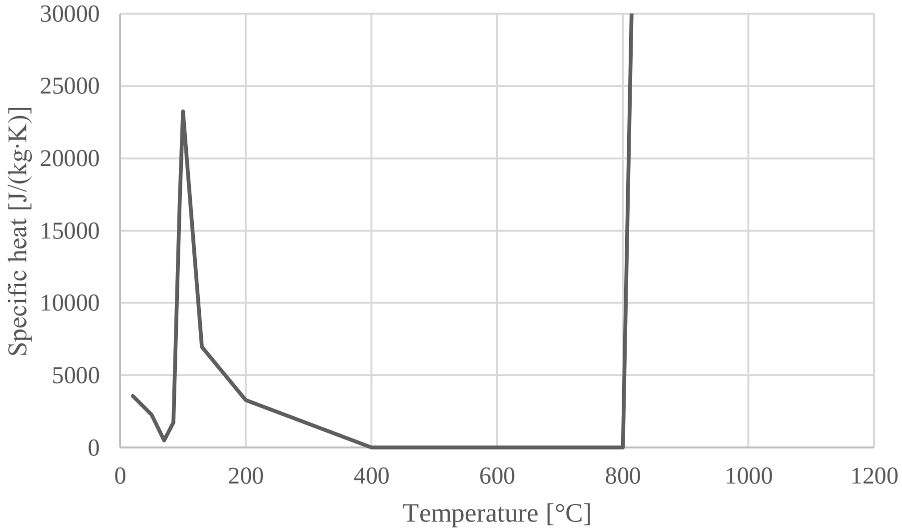

Figure 22: Specific heat of a loose fill cellulose fibre insulation

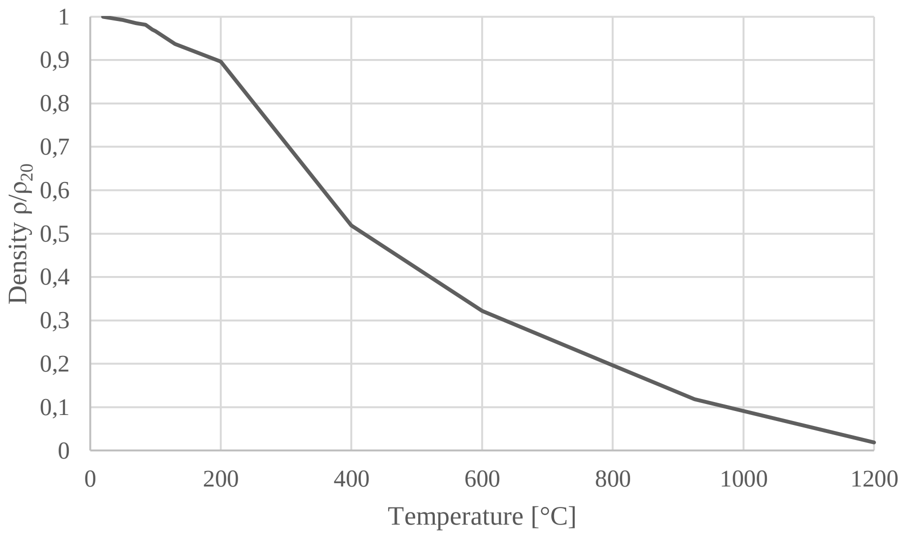

Figure 23: Specific heat of a loose fill cellulose fibre insulation

These thermal properties were developed from a backwards calculations using the MATLAB code from [8]. The thermal conductivity and specific heat were determined by calculations, the loss in mass was obtained from separate measurements.

The peaks around 100°C are the evaporation of free water as some moisture is present in the material. The model-scale fire tests were conducted with a chicken net reinforces with thicker steel bars at 10 cm intervals. The deflection of the fixation was quite minor throughout the test. The shrinkage of the material was noticeable from early on. No fall-off happened. The thermocouple measurements from between the insulation and the backing (wood fibre-) board were used as the reference for calibration.

Based on these graphs, it could be assumed that the material has effectively disappeared after 800°C. According to [14] lignin is the last wood component to degrade which can happen at as high as 900°C. Assuming that the material was impregnated with a flame retardant which lowers the charring temperatures, the complete disintegration of the cellulose fibre insulation could happen at 800°C as shown by the sharp increase of specific heat in Figure 22.

These thermal properties were used to simulate one horizontal test without a protective board conducted as part of an ongoing research project at TUM. The presented thermal properties severely underestimated the performance of the insulation material tested at TUM. The time until 300°C was reached behind the unprotected insulation layer differed by 17 minutes. The fixation topic is discussed further in the next subchapter.

Fixation of unprotected insulation

Fire tests following the ISO 834 [15] standard fire curve are the reference point for the determination of thermal properties via a backwards calculation. It seems to be best to have tests with the least amount of different materials included to minimise the number of variables. For insulation materials it is recommended to have tests with type F gypsum board as protection and unprotected tests where the insulation material is directly exposed to fire.

With loose fill insulations fastening is clearly an important topic as the fibres will not stick to the sides of the timber element with sufficient force to keep the insulation in place by itself. The insulation can stay in place by itself if I-joists are used instead of rectangular timber elements. Different fixation methods have been used, for example chicken net and timber laths. The latter is a low-cost and simple to install method which also gives good results in terms of preventing vertical deflection of the insulation in the horizontal tests.

The test with the Nordic cellulose fibre insulation used the chicken net and steel bars fixation, whereas timber laths with sufficient intervals were used in Germany. The difference in the results discussed previously might be because of the significantly better performance of the Central European bio-based fibrous insulation. Another possible reason is the fixation with timber laths which prevented the deflection and maybe even limited the contraction of the insulation.

Unprotected horizontal model-scale fire tests following the standard fire curve are recommended to develop the equations for the component additive method. This means that the fixation and technical details of testing combustible and bio-based insulation materials is an important topic which needs to be the focus of future research.

The aim of fire tests is to investigate the thermal performance of the material but also to observe the physical changes it goes through. Good fixation is necessary for keeping the material in place for long enough for it to be exposed for a sufficiently long time. In real life applications the fixation might be worse or non-existent altogether. Therefore, the possible fall-off of unfixed insulation is a topic for further research. Some possible solutions were discussed during the STSM but have not been thoroughly investigated.

Comparison of simulation software

Using different FE software packages to analyse the heat transfer in structures exposed to fire is a common occurrence. During this STSM two software were used for making a comparison of the features and limitations. The programs used are SAFIRv2014a1 and the 2017 program version of Ansys.

Initially the goal was to confirm that similar simulation approaches were used and to continue with parallel work to get more results. However, not everything goes to plan and many differences and nuances were found in the software.

Both use a system of input and output files which are plain text files. The input file is compiled by the user manually or by using a pre-processor (like Workbench for

Ansys). The output files are saved by the software after completing the simulation. Both files follow a specified structure.

Both Ansys and Safir are based on the Fourier' heat transfer differential equation and its numerical solutions. For this study, the assumption is that inside the prescribed elements thermal energy is transferred via solid conduction and on the interfaces of materials and air conduction and radiation are the heat transfer paths. Solid conduction is described by thermal properties of the material and heat transfer on the surfaces is accounted for by using appropriate surface coefficients.

As predicted, by using the same input parameters and simulation configurations the results finally were very similar between the software. Many crucial differences were identified in the process, however.

The prescription of thermal properties is rather straightforward in both software. The parameters are written in the text file for every temperature needed to describe the material with adequate accuracy.

The bigger differences were identified for surfaces. Radiation from the surface to the environment is described by using the appropriate value of emissivity. For most construction materials a value of 0.8 has been used. It ranges from 0 to 1 with 1 being a black body. For convective heat transfer near the surface, coefficients of convection must be input in both programs. These are different for the fire exposed and ambient side of the simulated structure. In some simulation approaches a lumped value of coefficient of convection and emissivity can be used on the unexposed side.

In the comparison it was discovered that in Ansys it is much easier to set different values of emissivity for the exposed and unexposed sides of the specimen. It uses a separate element for prescribing the existence of radiation and without it only convection is assumed. In Safir a similar approach might be possible by tricking the program by, for example, adding a paper-thin layer with 0 emissivity to the unexposed side.

The coefficients of convection (usually denoted as α) are also simplifications and generic values. The exact values are much too difficult to determine specific for each application and configuration and the current values in the Eurocodes give reasonable results. An extensive study on these coefficients and the “reality” of them was conducted by Werther as part of his Doctoral thesis at TUM [16]. Generally the values presented in the design standard [17] are conservative for the most part.

Another point of interest is that the time steps used by Ansys Workbench are very small in the beginning of the ISO 834 standard fire exposure. When uniform time steps are imposed (for example 5 seconds) the program displays a convergence error. This does not occur with Safir and a modified approach in Ansys. This means that the latter programs might use an enthalpy model where the *k-ρ-c* model is automatically converted to the enthalpy model for calculation. A comparison of these models and different simulation software was made by Werther et al [18].

Conclusions

The performed STSM was a success as a strong cooperation and connections were established. Continued work is already on the way and future collaborations will be appreciated.

The planned outcomes were not fully realised as fibrous and bio-based insulation materials proved to be a more complex topic than anticipated. This does not mean that the STSM was unsuccessful – the field of knowledge was expanded and the opportunity to cooperate with such an important research centre is invaluable to me.

The most important outcomes would definitely be the continued cooperation to study cellulose and wood fibre insulations at elevated temperatures. A collaborative article about the component additive method with contributions from experts from many research centres around Europe is being finalised and will be submitted to the COST 1404 special issue of Fire Safety Journal. The continued work should yield valuable input for the new redaction of the Eurocode 5 part 1-2 regarding the separating function and the contributions of bio-based insulation materials.

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