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Thermal conductivity of freely patterned pine and spruce needles

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Abstract

The aim of the study is to clarify the thermal conductivity coefficient of freely patterned pine and spruce needles. Heat flow measurements were made according to the two-factor experimental design and analysis of the full experimental design was made. The effect of moisture and coniferous tree species on the thermal conductivity coefficient was determined. The results show that different coniferous tree species needles hold different coefficients of thermal conductivity, which are influenced by various factors.

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1. Introduction

As the prices for energy resources rise, the costs of housing heating do also, and thus the question of refurbishing housing with the intent of improving thermal insulation is becoming more and more essential. Depending on the climate, both heating and cooling costs can be high. Use of thermal insulation either in the construction phase or refurbishment of housing can greatly decrease these heating and cooling costs. Since the 20^{th} century, the use of thermal insulation has become more and more popular along with concepts of sustainability and innovation. Sustainable and innovative construction (and refurbishment) is based on: reducing resource consumption, reusing resources, utilizing recycled materials, conserving the natural environment, removing toxins, ensuring economic efficiency by considering lifecycle costs and reinforcing quality.

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Thus, to achieve sustainable or "green" buildings, the integration and application of innovative technologies and products should be applied (e.g. through design and construction). [1, 2]

The most common thermal insulation materials are inorganic, affordable, available and easy to use. Recent studies have shown that some of the inorganic materials may have a negative impact on human health. [3] Thus it is important to use organic material for thermal insulation. [1]

Use of natural materials for thermal insulation is closely related to ecological building. Material choice in an ecological building takes into account factors like renewability, recyclability, etc. [3, 4]

Natural organic materials usually contain a higher specific heat capacity and higher moisture sensitivity than ordinary silicate materials. Organic materials are generally water vapour permeable and can accumulate moisture from the air.

Moisture accumulation can be viewed as favourable because organic materials have the ability to absorb excess moisture from the air and conversely release moisture if the humidity levels of the surroundings are lower. This mechanism of moisture capture and release leaves a positive influence on indoor air quality (especially in the winter when low indoor air humidity is experienced). The extent of these mechanisms depends on the specific structure and density of a material. In some cases the material is exposed to high humidity over the long term or is in contact with liquid which is no longer favourable. [3, 4]

For consumers who are environmentally aware, it is important to have the choice to use natural materials or materials with lower impact on human health or the environment in their life cycle. The lower impact of thermal insulation materials in the life cycle can be achieved by using natural materials or by implementing cleaner production principles in the manufacturing process. It is easier to reduce resource use and lower the overall impact of the product in the product design phase (as raw material use is not a valuable resource but one which is surplus).

Pine and spruce are the most common coniferous trees in the temperate climatic zone. In countries like Latvia, where more than half (54 %, 2013) [5] of its area are covered with pine forests, wood biomass is one of the most important resources. Wood biomass has a wide range of applications in local enterprises and is also exported.

Even though cutting technologies are developed and the cut wood volume is high, the volume of forestry residues is high and is usually discarded. This forestry residue consists of small twigs and coniferous residue (leaves and needles) and together consists of approximately 25 % of the total wood biomass. Forestry residue is usually used for producing wood chips for energetic purposes. It is common to leave forestry residue in piles at their location of origin to dry out naturally and for the needles to fall off. The presence of needles and resin is not favourable for wood chip production because, during the burning process they form slag together with the ashes. Thus the use of coniferous trees for wood chip production is not preferable. Most of the coniferous forestry residue is left in the forest unused and, overtime, naturally decomposes naturally. The only known use of coniferous forestry residue in Latvia is a production of extracts, but the production capacity is small (maximal capacity 800 t/a, actual capacity under 50 t/a [6]).

This means that every year thousands of tons of coniferous forestry residue is left to decompose instead of being used as a valuable resource. Approximately 700 thousand tons of coniferous forestry residue are created and wasted in the Baltic States every year.

The forestry residue amount is so large that its use in manufacturing should be evaluated from the economic and environmental point of view. One of the options for their use is as freely patterned thermal insulation material. This idea combines both the rational use of forestry residue and the production of a natural thermo insulation that should have less impact on human health and the environment during the life cycle. In order to make sure this idea is viable, an experiment to measure the thermal conductivity coefficient (and the impact factors) is carried out.

The paper presents an innovative idea for a potential, ecological thermal insulation material. The freely patterned coniferous material can be produced by cleaner production principles thus creating a solution to the forestry residue use problem.

2. Materials and methods

In order to evaluate the coniferous material, a Design of Experiment (DoE) was used which allows to determine the impact of main factors and to structure the overall experiment procedure.

The aim of experiment is to determine the thermal conductivity coefficient of freely patterned pine and spruce conifers. The main parameter in the experiment is the thermal conductivity as it describes the thermal insulation material performance the best. Two factorial experimental plans are used, where the factors are: type of conifers (spruce or pine) and drying time (1 month or 1 year). A total of four samples were used, the thermal conductivity coefficient of which was determined in three replicates (in order to increase the reliability of results).

The factor, type of coniferous tree species, is used to determine the differences between the two most popular species in a temperate climate zone (most popular species in Europe). In case any differences exist, the reasons for such differences should also be determined. Different coniferous tree species needles have similar chemical content and physical properties. The difference between pine and spruce needles are in size, form and placement on the branch - spruce needles are 10−25 mm and long, cross-section as square while pine needles are 20−70 mm long with round cross-section.

Factors such as drying process time and impact on thermal conductivity will show whether the moisture content in the coniferous influences the outcome. Thermal insulation materials usually are used for a long period of time approximately 20 year exploitation time for existing thermal insulation materials, so changes in the material itself may occur and influence thermal conductivity (assuming the insulation material life time is the same as the respective building's life time).

The first samples of biomass are collected during spring 2013 and dried for a year at room temperature (~20 °C). The rest of the samples are collected during spring 2014 and are dried for 1 month under the same conditions (~20 °C) until the needles fall off the branches.

Pine needles do not fall off the branches, so they were hand-plucked in order to gain wood free biomass (consisting only of needles).

In order to determine whether changes in biomass moisture content have an influence on thermal conductivity, moisture was measured prior to the experiment (measured moisture content in fresh needles was approximately 50 %). [7] The samples dried for only one month should contain more moisture than those dried for a year (author assumptions).

Table 1. Experimental plan with factor level in non-dimensional coordinate system

Factor	Nr.			
	1	2	3	4
A Tree species	Pine Min (−1)	Spruce Max (+1)	Pine Min (−1)	Spruce Max (+1)
B Drying period, months.	1 Min (−1)	12 Max (+1)	12 Max (+1)	1 Min (−1)

Table 1 represents the experimental plan; it also can be expressed with the actual factor values (instead of min, max). Based on this plan, 4 samples in tree replicates of freely patterned coniferous needles have been prepared.

The thermal conductivity coefficient is determined by heat flow measurements based on ISO 9869 standard "Thermal insulation – Building elements – In-situ measurements of thermal resistance and thermal transmittance" (1994) requirements. A hot box is used for heat flow measurements; it is made of extruded foam polystyrene (λ = 0.035 $\frac{W}{m \cdot K}$ thermal insulation plates. For the biomass input a hole (30 cm × 30 cm) was cut out of the top plane (later replaced with 50 mm thick pressed cardboard from both sides ($\lambda_{cardboard}$ = 0.23 $\frac{W}{m \cdot K}$). The hole is used for the biomass material input into the box.

During the measurement time, a lit light bulb heats up the inside of the box, as it is made of thermal insulation material and only insignificant amounts of heat escape. The box is then kept in an environment with a lower temperature than the inside of the hot box, thus simulating conditions of house (with higher temperature inside than outside). Using the temperature difference and heat flow measurements on the surface of the insulation material, thermal conductivity of the materials may be calculated [8, 9].

Table 2. Results of thermal conductivity experiments with calculation steps, where $\lambda_{sample\ (cardboard\ +\ needles)}$ - thermal conductivity of sample what consist of cardboard and needles, $\lambda_{extruded\ foam\ polystyrene}$ – thermal conductivity of extruded foam polystyrene, $\lambda_{sample\ (cardboard\ +\ needles)\ recalculated}$ – recalculated thermal conductivity of sample, what consist of cardboard and needles, proportionally theoretical thermal conductivity value of extruded foam polystyrene, R_λ – thermal resistance, $\lambda_{only\ needles}$ - thermal conductivity only of needles, $\lambda_{only\ needles\ recalculated}$ – recalculated thermal conductivity only of needles proportionally theoretical thermal conductivity value of extruded foam polystyrene

Sample number	Factor values A	Factor values B	x_k - $\lambda_{sample\ (cardboard\ +\ needles)}$, $\frac{W}{m \cdot K}$	$\lambda_{extruded\ foam\ polystyrene}$, $\frac{W}{m \cdot K}$	$\lambda_{sample\ (cardboard\ +\ needles)\ recalculated}$, $\frac{W}{m \cdot K}$	R_λ, $\frac{m^2 \cdot K}{W}$	$\lambda_{only\ needles}$, $\frac{W}{m \cdot K}$	$\lambda_{onlyneedles\ recalculated}$, $\frac{W}{m \cdot K}$
1	(−1)	(−1)	0.0703	0.0305	0.0807	0.6256	0.0657	0.0754
			0.0571	0.0306	0.0653	0.7701	0.0531	0.0607
			0.0785	0.0304	0.0903	0.6367	0.0807	0.0929
							Average	**0.076**
2	(+1)	(+1)	0.0397	0.0352	0.0395	1.1074	0.0367	0.0364
			0.0415	0.0354	0.0411	1.0580	0.0384	0.0379
			0.0427	0.0309	0.0482	0.7967	0.0321	0.0362
							Average	**0.037**
3	(−1)	(+1)	0.0741	0.0303	0.0854	0.5937	0.0694	0.0800
			0.0729	0.0303	0.0840	0.6029	0.0683	0.0787
			0.0599	0.0305	0.0688	0.7337	0.0558	0.0640
							Average	**0.074**
4	(+1)	(−1)	0.0338	0.0305	0.0387	1.3018	0.0311	0.0357
			0.0345	0.0340	0.0354	1.2743	0.0318	0.0327
			0.0375	0.0308	0.0426	1.1713	0.0346	0.0393
							Average	**0.036**

Measurements are carried out with heat flow measuring equipment unit Hukseflux DT01. The equipment has two heat flow sensors (attached to extruded foam polystyrene and the spruce or pine needle biomass sample) and 4 thermocouples (used for the inside and outside environment temperature measurements). The extruded foam polystyrene is used as a benchmark and to check that experimental measurements are correct (as the thermal conductivity coefficient of extruded foam polystyrene is known). Results of the measurements are displayed in Table 2.

The impact from cardboard to the thermal conductivity of the samples (needles with cardboard from both sides) is factored out of the impact factor consideration, because the theoretical thermal conductivity coefficient and thickness of cardboard is known. The simulation box was not kept in outside conditions in order to diminish the influence of the sun. In spite of this, the same samples show different thermal conductivity coefficient results. This is due to the accuracy of the instrument, the effects of wind, moisture and the density of freely patterned needles.

In order to ascertain that measurements are correct and significant, measurement error was evaluated for each sample. Calculated standard deviation and compliance with the normal distribution are shown in Table 3. With confidence reliability p = 95%, distribution coefficient τ_{95} = 1.412 with the number of measurements n equal to 3.

Obtained results show that the ratio of difference between the mean and the measured value of each measurement and the standard deviation is smaller than probability distribution coefficient at the 95 % confidence reliability. This means that all the measurements are reliable and can be used in calculations.

Table 3. Error of measurement

Sample number	Mean value of measurements, $x_{average}$	Standard deviation, s	Ratio, $\frac{\lvert x_k - x_{average}\rvert}{s} \leq \tau_p$
1	0.0686	0.01080	0.1544 1.0682 0.9138
2	0.0413	0.00151	1.0596 0.1324 0.9272
3	0.0690	0.00977	0.5256 0.4027 0.9284
4	0.0353	0.00197	0.7462 0.3901 1.1362

The lower the conductivity of a material, the more effective the thermal insulation material is. Judged by the average values, the best results are for spruce needle biomass that has been dried for a year (λ = 0.037 $\frac{W}{m \cdot K}$). Results of the one-month dried samples are very similar (λ = 0.036 $\frac{W}{m \cdot K}$). The results of pine needle biomass shows a similar trend - one year dried samples have lower thermal conductivity than one month dried samples (λ = 0.076 $\frac{W}{m \cdot K}$ and λ = 0.074 $\frac{W}{m \cdot K}$ respectively). In general, the pine needle biomass samples have higher heat conductivity meaning that spruce needle biomass thermal insulation materials would be more suitable.

Even though the moisture content in the needles that have been drying for a significantly longer time is lower, the difference is not that great to impact thermal conductivity. This means that, not only will the thermal insulation material not change its thermal conductivity characteristics over time (if we assume that loss of moisture until some point is still happening), but if the material is subjected to environment with higher moisture content, it will also notlose its ability to insulate.

3. Results and discussion

For the results of the thermal conductivity experiment, statistical analyses were conducted (including factor impact analysis, mathematical modeling and use of software Statgraphic).

The results prove that freely patterned pine and spruce needle biomass has a low thermal conductivity coefficient (λ_{spruce} = 0.0375 $\frac{W}{m \cdot K}$, λ_{pine} = 0.075 $\frac{W}{m \cdot K}$). This means that both of these materials could be utilized as thermal insulation.

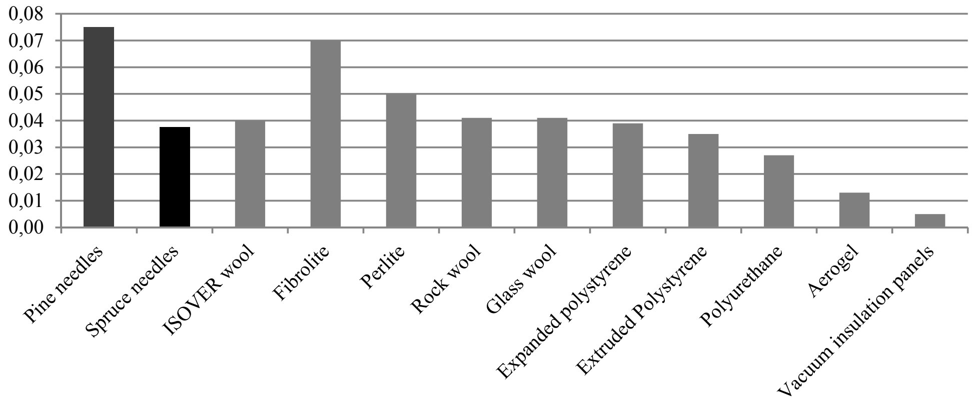

Fig.1. Thermal conductivity of organic and inorganic materials, $\frac{W}{m \cdot K}$.

Compared to already existing thermal insulation materials (see Fig. 1), spruce needle biomass shows as good or better performance than most. The performance is equal to such thermal insulation materials as extruded foam polystyrene, mineral and stone wool. These three are the most popular and commonly used insulation materials in the world. In case of pine, the performance is average in comparison to existing materials.

The difference between the performance of these two species of needle biomes can be explained by the differences in the size and form of the needles. These parameters influence the density, airflow and other parameters in the freely patterned material, in case of spruce the density of material is higher as the needles are smaller and create a smaller number of gaps for air to flow through.

In case of Latvia, pine tree growth is larger and more common than spruce, meaning that there is more of the biomass available for the production of thermal insulation material. As its thermal conductivity is higher, a solution should be found on how to better utilize these types of forestry residue - either by mixing the spruce and pine biomass together, or by reducing the gaps between the needles (changing the material from freely patterned to compress).

Freely patterned coniferous needle thermal insulation materials should be considered ecological and unique because:

- They are made of 100 % natural materials (spruce and pine needles without chemical components)
- Only local raw materials are used;
- Biomass wastes (forestry residue) are utilized;
- The production process is simple, waste-free and is not energy-intensive;
- During the life cycle of the material it does no harm neither the environment nor human health;
- While burning, the coniferous needles do not produce any harmful substances;
- The material is anti-allergic and does not cause inflammation or irritation;
- Non-renewable resources are not used in the production of material.

Even though the list of advantages for coniferous needle biomass use as freely patterned thermal insulation material is long, more analysis and experiments are needed to determine whether its performance is actually similar to existing thermal insulation materials. The aim of this article was to determine thermal conductivity, which is only one of the parameters that determine the validity of insulation. Other factors include: durability, moisture absorption during exploitation, granulometric content changes in time, safety and whether the material meets fire safety standards. The fact that untreated and dried needle biomass can catch fire easily should be taken into account and solutions should be found. For the produced material to stay ecological even after treatment, new solutions should be found. In addition, issues linked to the production and installation phase of the material should also be assessed their impact on the life cycle of the product. For example, a solution for the mechanical removal of pine tree needles from branches should be found in order to ensure the possibility to scale-up projects.

The first step of proving that the new material has low thermal conductivity has been made and further analysis of the subject should be continued as there is potential for a locally produced innovative and ecological insulation material.

4. Conclusions

The use of freely patterned coniferous tree needles as a thermal insulation material is a rational and innovative use of forestry residue.

Different species of trees provide different types of needles so the thermal conductivity of them varies. The thermal conductivity coefficient of freely patterned spruce is $\lambda = 0.0375\,\frac{W}{m \cdot K}$ and for freely patterned pine $-\ \lambda = 0.075\,\frac{W}{m \cdot K}$.

Freely patterned needle material is ecological and environmentally friendly in its life cycle as cleaner production principles can be applied.

The longer the spruce and pine needles are dried, the lower the moisture content. The drying period does not affect the performance of the insulation material.

The thermal conductivity of spruce needle material is similar to already existing thermal insulation materials, but further research is needed to ensure the performance and safety conditions of the new material.

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