WOOD FIBER INSULATION MATERIAL

Karlis Veitmans, **Uldis Grinfelds**
Latvia University of Agriculture
Latvian State Institute of Wood Chemistry
kaveit88@gmail.com

Abstract
As worldwide trends are changing gradually and sustainable resources economy and reduction of hazardous emissions are coming to the forefront, several industry sectors are forced to revalue their resource consumption. The main emphasis is currently placed on the recycling of by-products. One of the methods, definitely, includes burning of by-products to generate power, however it is not always the most efficient one. By-products must be used in the manner that ensures that they provide high added value for the operation of the company and are environmentally friendly. This research focuses on the use of the by-products of birch (*Betula*) veneer manufacturing, in order to obtain thermal insulation material. The following characteristics of the wood fiber insulation material were determined: thermal conductivity, water absorption, vapour permeability, and prototype reaction to fire. The characteristics of the obtained wood fiber thermal insulation material: thermal conductivity 0.038 $W \cdot m^{-1} \cdot k^{-1}$; water absorption 12 $kg \cdot m^{-2}$; the conformity of the material even to D fire reaction class was not determined. The principal conclusion: the wood fiber thermal insulation material conforms to the requirements set for thermal insulation materials.
Key words: use of by-products, wood fiber, cellulose fiber, thermal insulation.

Introduction

As the technologies develop and the range of possible solutions for improving the level of comfort increases, a steep surge in energy consumption has occurred. Climate change caused by the emissions of greenhouse gases is a topical problem that is currently faced by the European Union and the world. This problem is aggravated by the consumption of natural gas and oil resources.

The proportion of energy inefficient buildings in Latvia is still high. Buildings need to be insulated in order to save resources that have been used for the obtaining of thermal energy. A wide range of thermal insulation material is on offer nowadays, each of them having their own advantages and drawbacks. Only some of the offered thermal insulation materials are able to reach set requirements. Not only physical and mechanical indicators are significant for a contemporary consumer, but also the effect of the product on the environment. Manufacturing of thermal insulation materials could become one of the future challenges of Latvia's forestry industry. Forestry sector companies are investing in equipment to raise its efficiency and productivity. Unfortunately, the generation of by-products in the manufacturing process is inevitable. The companies of industry mainly use these by-products for the production of thermal energy or sell them to other companies. Export of these by-products is inefficient, since they are sold as low added value products. Further processing of by-products into thermal insulation materials is one of the solutions of increasing the income. The amount of exported woodchips and sawdust is 1,340,100 t (Ministry of Agriculture, 2014) in Latvia. Veneer manufacturing process is one of the leaders in the production of woodchips as a by-product. The type and proportion of wood processing side materials in the manufacturing of birch veneer is as follows (Ministry of Agriculture, 2005): sawdust; cellulose woodchips 6%; fuel and technological woodchips 39%; bark 10%, veneer cut-offs; lathe dust. This paper will review the possibilities of the manufacturing of thermal insulation material from by-products of plywood manufacturing process.

Three types of thermal transfer are presented in nature: thermal conduction – spread of heat within a solid body, liquid or gas; convection - spread of heat within liquid or gas, where the heat is transferred by heated molecules of the environment; irradiation - spread of heat in the premises by means of infra-red radiation. All three types of thermal conductivity are active simultaneously in nature, however, one of them always predominates. Thermal insulation materials are materials with high resistance to the heat transfer. Thermal insulation may consist of one material or a combination of several materials, which, if used and assembled correctly, reduces the flow of heat. Thermal insulation reduces the flow of heat in outdoors-indoors and indoors–outdoors direction as a result of high resistance to heat conductivity (Al-Homoud, 2004). Low thermal conductivity is the principal characteristic for thermal insulation material. Thermal conductivity is the time indicator of constant flow of heat (W) through a homogeneous material with the thickness of 1 m, in the direction that is perpendicular to isothermal sheets, which is caused by the temperature difference (K) within the sample. Thermal conductivity, (λ) is expressed as $W \cdot m^{-1} \cdot K^{-1}$ unit (Schiavoni *et al.*, 2016). Thermal conductivity directly depends on the temperature and moisture of the material. Thermal conductivity is the indicator of efficiency of any thermal insulation material. Thermal resistance is the indicator of the resistance of the material to heat transfer by inhibiting conductivity, convection and radiation. Thermal resistance is directly dependent on the thermal conductivity, thickness and density. The unit of thermal resistance is $m^2 \cdot K \cdot W^{-1}$ (Al-Homoud, 2004).

Thermal insulation materials resist the flow of heat thanks to multiple microscopic cells containing immobile air, which inhibit the transfer of heat by preventing the flow of air. The immobile air contained within the thermal insulation material, not the material itself, ensures the resistance to the movement of heat. The structure of closed cells ensures the reduction in thermal radiation. Thermal insulation materials that are developed on the basis of air cell principle, cannot exceed the thermal conductivity of air. Thermal insulation materials can be classified differently, however, two principal types of classification are generally used: by principle of operation and by chemical origin. Classification according to the principle of operation distinguishes the following thermal insulation materials: convective, reflective and vacuum insulation materials. According to chemical origin the materials are classified into: inorganic and organic insulation materials. Most commonly used inorganic insulation materials are rock wool and glass wool. Thermal conductivity for rock wool 0.033$W \cdot m^{-1} \cdot K^{-1}$ (Schiavoni *et al*., 2016) and for glass wool 0.043 $W \cdot m^{-1} \cdot K^{-1}$ (Stazi *et al*., 2014). Most commonly used organic insulation materials are expanded polystyrene – thermal conductivity 0.031 $W \cdot m^{-1} \cdot K^{-1}$, extruded polystyrene – thermal conductivity 0.032 $W \cdot m^{-1} \cdot K^{-1}$, polyurethane – thermal conductivity 0.022 $W \cdot m^{-1} \cdot K^{-1}$ and phenolic foam – thermal conductivity 0.018 $W \cdot m^{-1} \cdot K^{-1}$ (Schiavoni *et al*., 2016). All inorganic and insolation materials that are based on fossil fuels share same common problem: the production of those insulation materials causes significant pollution to environment, especially energy consumption during production and there is no renewable materials used. Also during the disposal of these insulation materials there are problems with recycling at the end of use (Binici & Aksogan, 2016). A solution for pollution and sustainable environment management is the use of green organic insulation materials and use of recycled materials. Nowadays most commonly used green organic insolation material is cellulose fibre, it is an eco-friendly thermal insulation material made from recycled paper fibres, material has good thermal conductivity properties – 0.037 $W \cdot m^{-1} \cdot K^{-1}$ (Hurtado *et al*., 2016). Similar insulation material is from wood fibres; usually it is produced from woodworking by-products such as wood chips, thermal conductivity – 0.038 $W \cdot m^{-1} \cdot K^{-1}$ (Geving, Lunde, & Holme, 2015a; Schiavoni *et al*., 2016). It is possible to find information about other similar insulation materials such as hemp, flax, sheep wool, cork and jute fiber - they all share approximately the same thermal conductivity – 0.038 $W \cdot m^{-1} \cdot K^{-1}$ (Schiavoni *et al*., 2016). The most common problem for this type of insulation materials is reaction to fire; without adding adjuvants to insulation materials they do not exceed class E (Schiavoni *et al*., 2016), it can be increased by using borax and boric acid as it is done while producing cellulose fiber insulation material (Hurtado *et al*., 2016).

This study concentrates on wood fiber insulation material from birch plywood production by-products. In literature it is possible to find articles where are tested hygrothermal properties of wood fiber based materials and concluded, that wood fiber based materials in the dry state can be considered as thermal insulators (Vololonirina, Coutand, &Perrin, 2014). Other studies are about investigations of moisture conditions in wood frame walls with wood fiber insulation, where wood fiber insulation material, in free flow and batt form, is compared with glass wool in different conditions during 200 day period, and it is concluded that wood fiber insulation performed similar to glass wool (Geving, Lunde, & Holme, 2015b). In all studies wood fiber origin was soft wood. Information about the use of hardwood as wood fiber insulation material in other studies is limited, also information about using of plywood production by-products to produce insulation materials is very narrow. The objective of the research is to determine the suitability of by-products of plywood manufacturing for the production of a wood fiber thermal insulation material.

Materials and Methods

The preparation of wood fiber is one of the most important processes. The raw materials for the production of wood fiber are by-products of veneer manufacturing: 'tears' 70% and 'cores' 30%.

Tears are pieces of irregular shape and thickness (the maximum thickness does not exceed 2.5 mm), which are generated in the scoring process of the veneer logs. Cores are cylinder-shaped part of the veneer log and are generated at the end of veneer log scoring. The tears and cores were transformed into woodchips. Single-stage TMP (Thermo mechanical pulp) process was used to obtain wood fiber from woodchips. Parameters of defibration were: 145 °C temperature, steam pressure 0.4 MPa. In order to improve the properties of wood fiber as an insulation material, borax and boron were added. Borax - sodium tetraborate decahydrate $Na_2B_4O_7 \cdot 10H_2O$. Borax was added to the material in order to improve its biological protection. Boric acid H_3BO_3 - is used as a fire retardant. Chemicals were added in amount of 12% (boric acid) and 7% (borax) of thermal insulation material. The application of wood fiber was performed in dry form, by dividing them into categories by density. In order to determine the conformity of the tested material to the requirement for thermal insulation materials, it was compared to commercially available cellulose fiber thermal insulation material. Density groups of thermal insulation material samples were: 40 kg·m^{-3}; 50 kg·m^{-3}; 60 kg·m^{-3}.

The study was conducted at the Latvia University of Agriculture and the Latvian State Institute of Wood Chemistry from 09.01.2012 to 04.01.2013.

Thermal conductivity

Thermal conductivity was determined in accordance to LVS EN 12667 standard using HFM 436 Lambda device. Three samples from each density groups were prepared according to the specification of the device.

Water absorption

Water absorption of thermal insulation material was determined in accordance to LVS EN 1609 standard. 200×200×100 mm samples were prepared in order to perform tests. Considering the fact that the standard is applicable for thermal insulation materials of a sheet shape, it was adapted to the properties of bulk thermal insulation material. A surface box with the sieve (sieve opening diameter 4 mm) was prepared. The dimensions of the box were chosen to form samples according to the standard. The sample was embedded in the sieve box and submerged into water. Sample was removed from the tank after 24 hours and placed on a 45 degree sloped surface and kept there for 15 minutes. After the performance of these operations, the sample was weighed and its mass m_{24} was determined. Five samples of each density group of insulation materials were tested.

Vapour permeability

Vapour permeability was determined according to LVS EN 12086. Considering its applicability it was adjusted for bulk thermal insulation materials by preparing a specific tank. Glass vessels filled with the saturated solution of KCl (potassium chloride) were placed at the bottom of the tank. The samples for the test were prepared from a 100 mm diameter and 100 mm high pipe by attaching a glass fiber sieve at the bottom of the pipe, which helped to hold the bulk material. The vessel with P_2O_5 (phosphorus pentoxide) was placed under the pipe. Five samples of each density groups were weighed and placed in the tank. After 24 hours samples were removed and weighed. In order to determine vapour permeability, the mathematical calculation indicated in LVS EN 12086 is used.

Conformity of the material to fire reaction class

Sample of insulation material was prepared according to standard LVS EN 13823. To adapt standard requirements for bulk thermal insulation material, wires were used to hold the tested material. Data collected were analysed with an appropriate statistical software program.

MS Excel programme package was used in order to statistically process the obtained results using standard deviation, arithmetic mean value and method of descriptive statistics.

Results and Discussion

Thermal conductivity

Thermal conductivity is one of the most important properties of thermal insulation materials (TIM).

The numerical value of thermal conductivity quotient (TCQ) increases with the increase in the

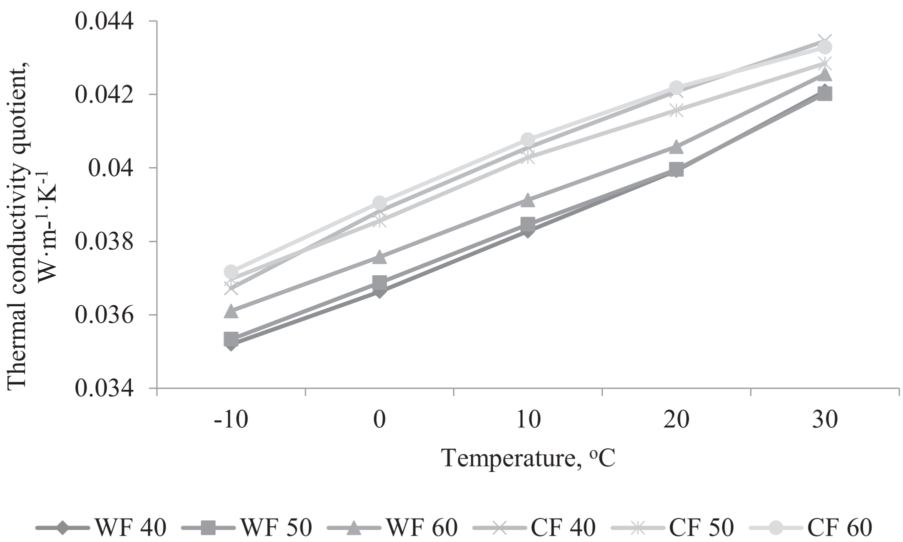

Figure 1. Thermal conductivity of thermal insulation materials depending on their density and temperature: WF – wood fiber; CF – cellulose fiber.

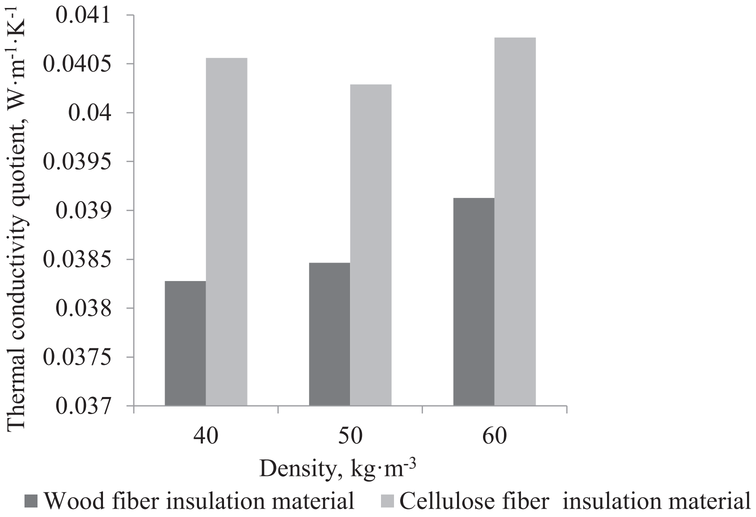

Figure 2. Comparison of thermal conductibility quotient by thermal insulation material.

temperature (Fig.1). The increase in numerical value of TCQ of TIM points to deterioration of their properties, in this case, the higher the temperature, the larger the amount of heat that the TIM conducts. The TCQ for wood fiber TIM with the density of 40 kg·m^{-3} increases by 0.0069 W·m^{-1}·K^{-1} or by 20%, if the temperature increases from -10 to + 30 °C, respectively: at the density of 50 kg·m^{-3} it grows by 0.0067 W·m^{-1}·K^{-1}, or 19% and at 60 kg·m^{-3} – by 0.0064 W·m^{-1}·K^{-1}, or 18%. In a cellulose fiber TIM with the density of 40 kg·m^{-3} the TCQ increases by 0.0067 W·m^{-1}·K^{-1} or by 18%, respectively: at the density of 50 kg·m^{-3} it grows by 0.0059 W·m^{-1}·K^{-1}, or 16% and at 60 kg·m^{-3} – by 0.0061 W·m^{-1}·K^{-1}, or 16%. The conclusion can be drawn that the higher is the density, the slower is the increase in TCQ as the percentage of the initial TCQ.

The comparison of TCQ of WF CIM by the density of application thereof allows the conclusion that the applied sample with the density of 60 kg·m^{-3} has a numerically higher value of TCQ. This means that excessive compacting of WF is inefficient because at a higher consumption of material the properties of thermal insulation material deteriorate. The comparison of TCQ of CF TIM by their density allows the conclusion that the embedded samples with the density of 40 and 60 kg·m^{-3} have a numerically higher value of TCQ. This means that too low, as well as too high compacting of applied CF in the TIM is inefficient.

The TCQ of a material is determined at the temperature of 10 °C. The comparison of both materials graphically (Fig.2) demonstrates that the thermal conductivity of WF TIM is lower. In the density group of 40 kg·m^{-3} TCQ of WF is 0.0383 W·m^{-1}·K^{-1}, that of CF is 0.0406 W·m^{-1}·K^{-1}, which is by 6% higher. In the density group of 50 kg·m^{-3} the TCQ of WF is 0.0385 W·m^{-1}·K^{-1}, that of CF is 0.0403 W·m^{-1}·K^{-1}, which is by 5% higher. In the density group of 60 kg·m^{-3} the TCQ of WF is 0.0391 W·m^{-1}·K^{-1}, that of CF is 0.0408 W·m^{-1}·K^{-1}, which is by 4% higher. It can be concluded that as the temperature increases, the thermal conductivity of both materials tends to be equalised, but at the temperature of 10 °C CF TIM has higher capacity to conduct heat. Determined values of thermal conductivity quotient of wood fiber insulation material are similar to organic thermal insulation materials 0.038 W·m^{-1}·K^{-1} and similar to commonly used nonorganic insulation materials rock wool 0.033W·m^{-1}·K^{-1} (Schiavoni *et al*., 2016) and glass wool 0.043 W·m^{-1}·K^{-1} (Stazi *et al*., 2014).

Water absorption

Upon mutual comparison of the differences in average values of water absorption (Fig.3) of WF TIM and various densities of thermal insulation material application, it can be observed that water absorption for: (distribution marks represent standard deviation) WF 40 – 7.87±0.18 kg·m^{-2}; WF 50 – 11.37 ± 0.05 kg·m^{-2}; WF 60 – 16.37 ± 0.20 kg·m^{-2}; CF 40 – 16.74 ± 0.23 kg·m^{-2}; CF 50 – 23.60 ± 0.28 kg·m^{-2}; CF 60 – 16.37 ± 0.51 kg·m^{-2}.

It can be observed that: WF 40 with WF 50 – material with the density of application of 50 kg·m^{-3} absorbs by 3.5 kg·m^{-2} or 44% more water. Water absorption for: WF 40 – 7.87 ± 0.18 kg·m^{-2}; WF 50 – 11.37 ± 0.05 kg·m^{-2}; WF 60 – 16.37 ± 0.20 kg·m^{-2}; CF 40 – 16.74 ± 0.23 kg·m^{-2}; CF 50 – 23.60 ± 0.28 kg·m^{-2}; CF 60 – 16.37 ± 0.51 kg·m^{-2}. WF 40 with WF 60 – material with the density of application of 60 kg·m^{-3} absorbs by 8.5 kg·m^{-2} or 108% more water; WF 50 with WF 60 - material with the density of application of 60 kg·m^{-3} absorbs by 5 kg·m^{-2} or 44% more water. Upon the comparison of WF TIM with CF TIM at similar densities of application, the average values

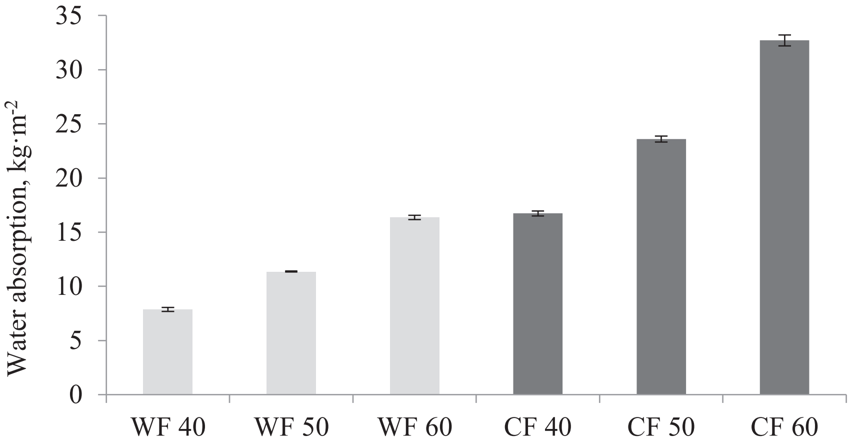

Figure 3. Summary of water absorption results:
WF – wood fiber; CF – cellulose fiber.

of water absorption results were: WF 40 with CF 40 – the water absorption of CF TIM with the density of 40 kg·m^3 is by 9 kg·m^{-2} or 113% higher than that of WF TIM of the same density; WF 50 with CF 50 – the water absorption of CF TIM with the density of 50 kg·m^{-3} is by 12 kg·m^{-2} or 108% higher than that of WF TIM of the same density; WF 60 with CF 60 – the water absorption of CF TIM with the density of 60 kg·m^{-3} is by 16 kg·m^{-2} or 100% higher than that of WF TIM of the same density.

Vapour permeability

Water vapour permeability (Fig. 4) shows the multiplication of the conducting capacity and thickness of the tested sample. Water vapour permeability is the property of material for homogeneous products. It is equal to the amount of water vapour, which is transferred within a unit of time through a unit of area of the product, given the vapour pressure between the planes of the item and item thickness (Vulans, 2011).

Upon mutual comparison of WF 40 with WF 50 (distribution marks represent standard deviation) – the water vapour permeability of the material with the density of 40 kg·m^{-3} is by 0.06 mg·h·m^{-1}·Pa^{-1} or 24% higher; WF 40 with WF 60 – the water vapour permeability of the material with the density of 60 kg·m^{-3} is by 0.02 mg·h·m^{-1}·Pa^{-1} or 6% higher; WF 50 with WF 60 – the water vapour permeability of the material with the density of 60 kg·m^{-3} is by 0.08 mg·h·m^{-1}·Pa^{-1} or 32% higher. Upon mutual comparison of WF 40 with CF 40 – the water vapour permeability of the WF TIM with the density of

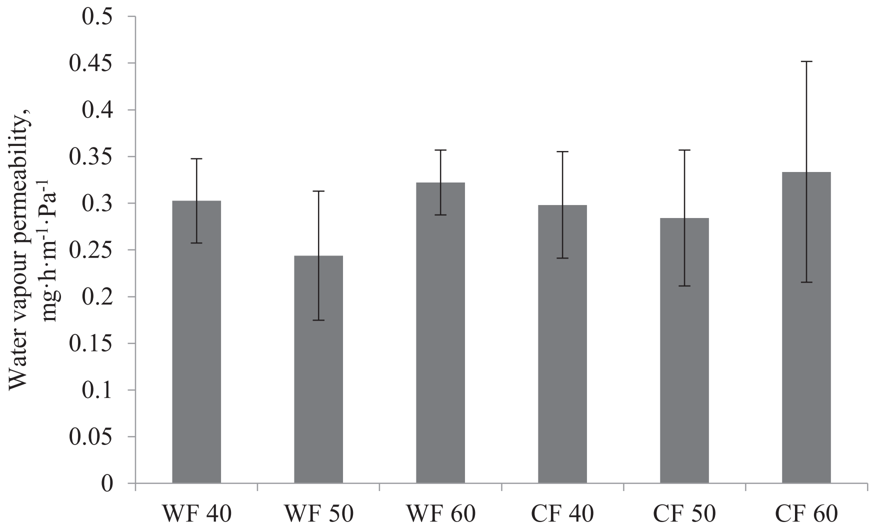

Figure 4. Water vapour permeability depending on density and insulation material:
WF – wood fiber; CF – cellulose fiber.

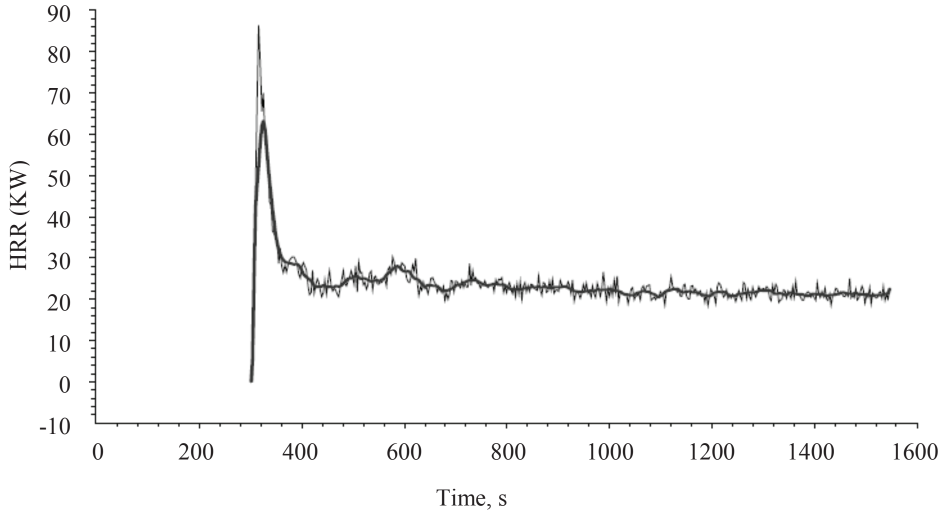

Figure 5. Changes in the heat release rate (HRR) of wood fiber thermal insulation material with time.

40 kg·m^{-3} is by 0.004 mg·h·m^{-1}·Pa^{-1} or 1% higher; WF 50 with CF 50 – the water vapour permeability of the CF TIM with the density of 50 kg·m^{-3} is by 0.04 mg·h·m^{-1}·Pa^{-1} or 17% higher; WF 60 with CF 60 – the water vapour permeability of the CF TIM with the density of 60 kg·m^{-3} is by 0.01 mg·h·m^{-1}·Pa^{-1} or 4% higher. The conclusion can be made that samples in the density group of 50 kg·m^{-3} demonstrate lower water vapour permeability.

Fire reaction class

All construction products must have known fire reaction parameters, which determine the reaction of the material to flame exposure.

Fire reaction is the capacity of the material to catch fire, the speed of fire spread and combustion capacity. There are 7 fire reaction classes depending on the type of material, which are classified according to LVS EN 13501-1 standard. The dynamic change of material combustion is characterised by the heat release rate for the wood fiber thermal insulation material (Fig. 5).

A rapid increase in the heat release rate is observed at the moment of catching flame. The maximum heat release rate is reached within approximately 30 s. After rapid increase in heat release rate a comparatively steep decrease in heat release rate is observed, and in the following phase of burning the heat release rate remains constant.

The speed of fire spread is characterised by fire growth rate (Fig. 6).

The most important parameter that characterises the burning of material and its influence on the overall development of fire is the total heat release (THR). Like heat release rate, the changes of FIGRA index demonstrate considerable increase at the beginning of the test, followed by rapid decrease. The total heat release THR increases gradually without steep peaks.

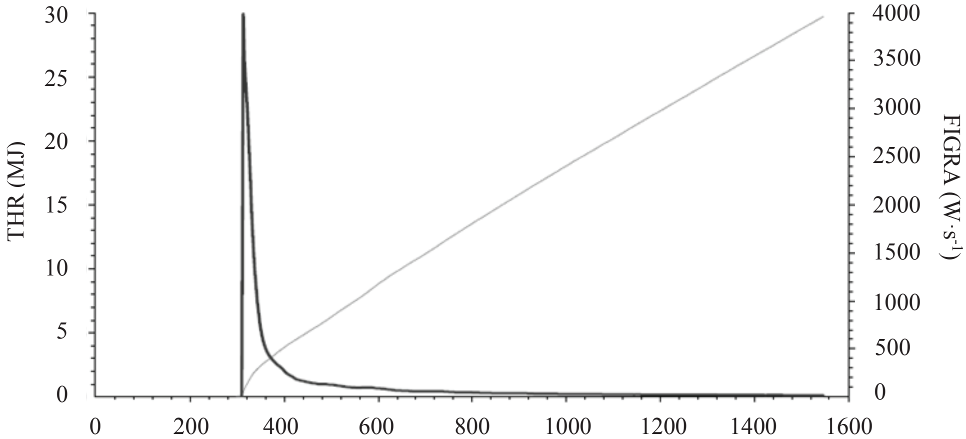

Figure 6. Changes in the fire growth rate (FIGRA) and total heat release (THR) with time:
FIGRA; THR .

The rapid increase in the heat release rate (HRR) and fire growth rate (FIGRA) index and the following drop in these indicators can be explained by the high surface area of the insulation material, as the wood fiber creates a fluffy surface that rapidly catches fire, when it has burned off, the flame disappears. After the performance of this experiment, the conformity of wood fiber thermal insulation material to minimum requirements of D fire reaction class could not be confirmed.

The fact that natural settlement of the thermal insulation material was not researched can be mentioned among the weak points of the research, which could prove to be a significant problem, considering the structure of the insulation material. In order to increase the thermal reaction class, the permeating of the fibers with fire retardant and fungicide solutions can be performed in order to ensure better binding of the chemicals with the fiber, as a result of which a higher fire safety class could be reached.

Conclusions

1. Birch wood fiber can be used to obtain a high quality thermal insulation material, which can be applied by using the spraying technology and used for thermal insulation of private buildings.
2. Thermal conductivity quotient of wood fiber thermal insulation material with density: 40 $kg \cdot m^{-3}$ is 0.0383 $W \cdot m^{-1} \cdot K^{-1}$; 50 $kg \cdot m^{-3}$ is 0.0385 $W \cdot m^{-1} \cdot K^{-1}$; 60 $kg \cdot m^{-3}$ is 0.0391$W \cdot m^{-1} \cdot K^{-1}$. Value of thermal conductivity quotient of wood fiber thermal insulation material is characteristic of organic thermal insulation materials and similar to commonly used nonorganic insulation materials - rock wool and glass wool.
3. Wood fiber thermal insulation material demonstrates high water absorption capacity of 7.87 ± 0.18 $kg \cdot m^{-2}$ with density 40 $kg \cdot m^{-3}$; 11.37 ± 0.05 $kg \cdot m^{-2}$ with density 50 $kg \cdot m^{-3}$; 16.37 ± 0.20 $kg \cdot m^{-2}$ with density 60 $kg \cdot m^{-3}$, however, it is lower than that of cellulose fiber thermal insulation material.
4. During the fire reaction class determining experiment, the wood fiber thermal insulation material failed to demonstrate the conformity even to D class.
5. All parameters obtained during the experiments are directly dependent on the density of material application. The optimum density of wood fiber material application is 40 $kg \cdot m^{-3}$, both, in terms of economic use of wood fiber and technical thermal parameters.

Acknowledgements

The authors express their thanks to companies: Latvijas Finieris, Vides Tehnika. Also thanks to Latvian State Institute of Wood Chemistry and the Department of Wood Processing of the Latvia University of Agriculture for assistance in some of the experiments.

References

1. Al-Homoud, M. (2004). Performance characteristics and practical applications of common building thermal insulation materials. *Building and Environment*, 40, 353-366.
2. Binici, H., Aksogan, O. (2016). Eco-friendly insulation material production with waste olive seeds, ground PVC and woodchips. *Journal of Building Engineering*. 5. 260-266.
3. Gevinga, S., Lundea, E., & Holmeb, J. (2015a). Insulation materials for the building sector: A reviewand comparative analysis. 6th International Building Physics Conference, IBPC 2015 (pp. 1455-1460). Elsevier Ltd.
4. Gevinga, S., Lundea, E., & Holmeb, J. (2015b). Laboratory investigations of moisture conditions in wood frame walls with wood fiber insulation. 6th International Building Physics Conference, IBPC 2015 (pp. 1455-1460). Elsevier Ltd.
5. Hurtado, P.L., Rouilly, A., Vandenbossche, V., & Raynaud, C. (2016). A review on the properties of cellulose fibre insulation. *Building and Environment.* 96. 170-177.
6. Latvian national standardization institution. (2002). Thermal insulating products for building applications - Determination of short term water absorption by partial immersion. LVS EN 1609. Latvia, Riga.
7. Latvian national standardization institution. (2002). Thermal insulating products for building applications - Determination of water vapour transmission properties. LVS EN 12086. Latvia, Riga.
8. Latvian national standardization institution. (2002). Thermal performance of building materials and products - Determination of thermal resistance by means of guarded hot plate and heat flow meter methods - Products of high and medium thermal resistance. LVS EN 12667. Latvia, Riga.
9. Latvian national standardization institution. (2010). Fire classification of construction products and building elements - Part 1: Classification using data from reaction to fire tests. LVS EN 13501-1. Latvia, Riga.

10. Ministry of Agriculture of the Latvian republic. (2014). *Meža nozares produkcijas eksports no Latvijas* (Forest products exports from Latvia). Latvian Government Publishing Service. (in Latvian).
11. Ministry of Agriculture of the Latvian republic. Forest Development Fund. (2005). *Koksnes pārstrādes blakusproduktu kvalitātes un to izmantošanas alternatīvu izpēte Latvijas uzņēmumos* (Wood processing by-product quality and use alternatives in Latvian companies). Jelgava 76 lpp. (in Latvian).
12. Stazia, F., Tittarellib, F., Politia, G., Di Pernac, C., & Munafò, P. (2014). Assessment of the actual hygrothermal performance of glass mineralwool insulation applied 25 years ago in masonry cavity walls. *Energy and Buildings*. 68. 292-304.
13. Vololonirina, O., Coutand, M., & Perrin, B., (2014). Characterization of hygrothermal properties of wood-based products – Impact of moisture content and temperature. *Construction and Building Materials*. 124 (63). 223-233.
14. Vulans, A. (2011). *Mitruma režīma konstrukcijās ar putu polistirolu siltinātās ēkās aprēķins* (Calculation of Humidity regime structures with foam polystyrene insulated buildings). Riga: Latvian Ministry of Economy. (BFA-EPS/11/01) (in Latvian).