

Article

Experimental Assessment of the Thermal Conductivity of Basalt Fibres at High Temperatures

Yuri Vankov ¹, Elvira Bazukova ¹, Dmitry Emelyanov ², Alexander Fedychin ³, Olga Afanaseva ⁴ ,
Irina Akhmetova ^{5,*} and Umberto Berardi ⁶ 

¹ Institute to Heat Power Engineering, Kazan State Power Engineering University, 420066 Kazan, Russia; yuv4nkv@yandex.ru (Y.V.); elvirabazukova@yandex.ru (E.B.)

² Chemical Department, Kazan (Volga Region) Federal University, 420008 Kazan, Russia; dmaemelyanov@kpfu.ru

³ Energy Efficiency and Hydrogen Technology Department, Power Engineering Institute, National Research University Moscow, 111250 Moscow, Russia; fedychinav@yandex.ru

⁴ Institute of Energy, Peter the Great St. Petersburg Polytechnic University, 195251 St. Petersburg, Russia; eccolga@mail.ru

⁵ Institute of Digital Technologies and Economics, Kazan State Power Engineering University, 420066 Kazan, Russia

⁶ Department of Architectural Science, Ryerson University, Toronto, ON M5B 2K3, Canada; uberardi@ryerson.ca

* Correspondence: irina_akhmetova@mail.ru

Abstract: This paper investigates fibrous thermal insulation materials of various densities to assess the change in their thermophysical properties at high temperatures. The thermal conductivity of fibrous thermal insulation materials is discussed as a function of the temperature in the range from 50 °C to 500 °C. It is shown that the thermal insulating properties depend not only on the physical properties of the material (e.g., density or diameter of fibres), but also on the geometric parameters of the structure and on the orientation of the fibres. The influence of high temperatures on the mass change of fibrous materials associated with the burnout of synthetic binders is shown. These features should be taken into account during the design of thermal insulation operating at high temperatures to provide the optimal selection of the material and to guarantee the stability of their thermal properties.

Keywords: heat losses; district heat network; thermal insulation; basalt fibre; thermogravimetry; thermal conductivity



Citation: Vankov, Y.; Bazukova, E.; Emelyanov, D.; Fedychin, A.; Afanaseva, O.; Akhmetova, I.; Berardi, U. Experimental Assessment of the Thermal Conductivity of Basalt Fibres at High Temperatures. *Energies* **2022**, *15*, 2784. <https://doi.org/10.3390/en15082784>

Academic Editors: Mark Bomberg and Bertrand Lenoir

Received: 22 February 2022

Accepted: 26 March 2022

Published: 11 April 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The development of materials with improved thermal insulation is a topical issue of current material science research. For example, super-insulating materials with extremely low thermal conductivity have experienced increasing diffusion. The use of porous thermal insulation material based on glass, plasticiser, and organic additives for thermal insulation of pipelines of heating mains and utilities have been extensively discussed in recent years [1,2].

The behaviour of insulating materials for high-temperature supply systems, such as district heating networks, has received increasing interest [3]. Field tests found that the actual heat losses exceed the standard values by 1.21–1.35 times in heat networks [3]. These results emphasise the need to develop durable materials with a stable behaviour even at temperatures of several hundred Celsius degrees.

The work [4] proposed an experimental installation of an original design for measuring the actual temperatures of the heat carrier and soil parameters in terms of the nature of the distribution of the heat flux density from the heat network. During the experimental studies, the places of coolant leakage into the ground were identified together with the sections of heat pipelines with an unsatisfactory state of thermal insulation materials. A similar problem

was addressed by researchers from the Chalmers University of Technology comparing the results of numerical modelling and measurements using non-destructive testing [5,6].

Researchers from Donyan University [7] conducted an experimental and theoretical study of the thermophysical properties of polyethylene foam insulation to determine the fire resistance of thermal insulation material and state that the insulation of pipes made of foamed polyethylene complies with classes B, C, and D, according to the fire growth rate index-FIGRA (ISO 25762:2009).

The work [8] presents possible options for reducing heat losses in the existing heat network in Central Europe. Simulations of five different options were conducted, offering different ways of laying pipelines, temperature schedule, and thickness of thermal insulation. Heat loss analysis was carried out for different operating temperatures of the heating system and two different cross-sectional shapes of heat insulation. Based on the results of the work performed, an original layout was proposed, combining several pipelines. In [9], this topic was developed further and a variant of the layout of a heat network with four pipes in one pre-insulated casing (two pipes for heating and hot water supply) was discussed. The authors claimed that such pre-insulated pipes significantly reduce heat loss, increase the environmental friendliness of the coolant transportation compared to four single pre-insulated pipes while reducing the cross-sectional area of the thermal insulation. Thus, the production of effective thermal insulation with low thermal conductivity is an urgent task, which requires a comprehensive solution both in terms of material selection and layer thickness and layout of pre-insulated pipes.

2. Relevance of the Research

Half of the total produced heat energy in the Russian Federation is consumed for the needs of the industry, mainly in the form of water vapour [10]. The largest consumers of heat are enterprises of chemical, petrochemical, fuel, metallurgical, manufacturing, and food sectors [11]. Many energy-intensive industries have an extensive power supply system. For such industries, measures aimed at reducing heat losses during the energy transportation are critical. For thermal insulation of high-temperature heat carriers, fibrous materials, such as mineral wool, represents up to 90% of total thermal insulation [12].

The efficiency of heat and energy transportation systems in terms of reducing heat losses depends on the efficiency of the thermal insulation. The procedure for assessing the standard heat losses through thermal insulation structures of pipelines was approved by the Ministry of Energy of the Russian Federation with the resolution No. 325 on 30 December 2008 [13]. This stressed that the long-term operation at high temperatures changes the structure of the thermal insulation material, which leads to an increase in the effective thermal conductivity. The actual thermal conductivity in comparison to the nominal one can increase by 60%, depending on the operating conditions, mainly the operative temperature [14,15].

Some works have already looked at the stability of thermal insulation materials in buildings [16–18]. However, the operating temperature of thermal insulation materials used in energy-supply industries to insulate the pipelines may be different [19–21].

When choosing the insulation material, it is necessary to take into account its ability to maintain its stable behaviour for a long time, also taking into account the operating conditions [22,23]. This work aims to study experimentally the thermophysical properties of fibrous thermal insulation materials, focussing on the thermal conductivity of a basalt fibre as a function of density and temperature. Basalt is the most common material in Russian pipelines, but the value of the present investigation can also be replicable to other materials.

3. Methodology

Fibrous thermal insulations of various densities were examined to assess the change in the material thermophysical properties under the influence of high temperatures. The heat-shielding properties of fibrous thermal insulation materials depend not only on the

physical and mechanical properties of the material (density, thermal conductivity, and diameter of fibres) and temperature regimes of their operation, but also on the geometric parameters of the structure and orientation in space [24].

The changes in the coefficient of thermal conductivity at elevated temperatures were studied. The thermal conductivity of products of cylindrical shape was measured in accordance with the Russian State Standard GOST 32025 “Thermal insulation. Method for determining the characteristics of heat transfer in factory-made cylinders in a stationary thermal regime”. This standard is largely based on the standard ISO 8497 “Thermal Insulation—Determination of steady-state thermal transmission properties of thermal insulation for circular pipes” [25]. An experimental setup was created and has been described in [26,27].

The study of thermal conductivity in fibrous thermal insulation materials by the method of stationary thermal regime on flat samples was carried out in accordance with the Russian State Standard GOST 7076-99. This standard is harmonised with the standards ISO 7345 and ISO 9251 in terms of terminology and complies with the main provisions of ISO 8301, ISO 8302, which establish methods for determining thermal resistance and effective thermal conductivity using a device equipped with a heat meter and a device with a hot security zone [28]. An experimental setup was assembled with an asymmetric layout of heat meters. The setup consists of: a ceramic flat heater (1) placed between two metal plates (2), adjustable in the height of the upper clamping metal plate (3) to fix the investigated sample (4), chromel-alumel thermocouples (6), heat flow sensors (5), metal protective casing (7), thermostat, and analogue-to-digital converter. The measurement scheme is shown in Figure 1.

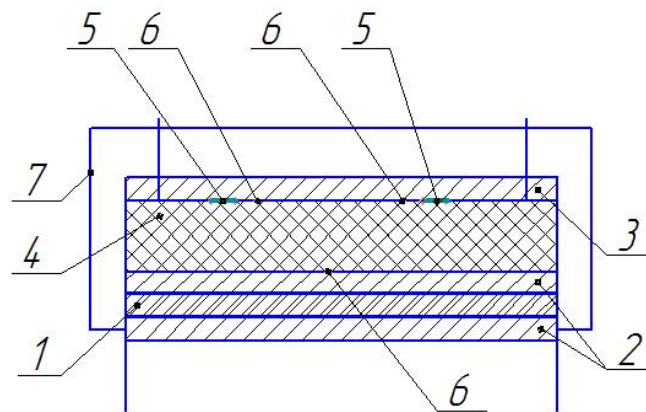


Figure 1. The scheme of the measurement setup: 1—heater, 2—hot plate, 3—cold plate, 4—sample, 5—heat flow sensors, 6—chromel-alumel thermocouples, 7—metal protective casing.

The maximum power of the heater was 2500 W; the operating temperature was up to 400 °C. To measure the surface temperature of the insulating material, chromel-alumel thermocouples with an operating temperature range from −200 to +1100 °C were used. To measure the heat flux density, high-temperature heat flux sensors with the following characteristics were installed on the surface of the thermal insulation material under study: size 52 × 10 mm, thickness 2 mm, measuring range 10–1000 W/m², time constant no more than 10 s, effective thermal conductivity coefficient 0.5 W/(m·K). The thermal resistance of the heat flow sensor with a thickness of 2 mm was 0.0166 (m²·K)/W. This resistance introduced a measurement error of no more than 3%.

The investigated samples were placed on the heater plate (2). The side faces of the sample were covered with a layer of thermal insulation material, the thermal resistance of which were not less than the thermal resistance of the sample. Before testing, the samples were dried to constant weight. A sample was considered dried to constant weight if the loss of its weight after another drying for 0.5 h did not exceed 0.1%. The received signal was processed using the developed software in the LabVIEW software package [29].

The thermal conductivity of the material under study was determined after the establishment of a stationary thermal regime in the measurement zone according to Formulas (1) and (2). The thermal conductivity was determined from Fourier's formula:

$$\lambda = \frac{q}{(t_1 - t_2)} \cdot \delta, \quad (1)$$

where q is the density of the heat flux, W/m^2 ; δ is the thickness of the studied sample of thermal insulation, m; $(t_1 - t_2)$ is the difference in the temperatures of the facial faces of the test sample, measured using thermocouple, °C.

For samples of a cylindrical shape, the thermal conductivity of the test material was determined by the following formula:

$$\lambda = \frac{q_L \cdot \ln \frac{d_2}{d_1}}{2\pi \cdot (t_1 - t_2)}, \quad (2)$$

where q_L is the linear heat flux density, W/m ; d_1 is the outer diameter of the pipe, m; d_2 is the outer diameter of a cylindrical sample, m; t_1 is the temperature on the surface of the heat-insulated pipe, measured using thermocouples, °C; t_2 is the temperature on the outer surface of the thermal insulation, measured with thermocouples, °C.

The heat-shielding properties of thermal insulation materials are associated with the peculiarities of their structure. All thermal insulation materials are a variety of gas-filled systems. The gas phase is enclosed in cells completely or partially isolated, or communicating with each other. Fibrous materials consist of a gas phase enclosed in an anisometric volume, which is formed by elementary filamentous structures fixed mechanically or with a binder. Taking into account the peculiarities of the structure of fibrous thermal insulation materials, the transfer of heat in thermal insulation materials includes the transfer of heat by conductive thermal conductivity, radiation, and convection. It can be carried out in the following ways:

- by thermal conductivity of the solid skeleton, which forms the porous structure;
- by thermal conductivity of gas in pores and capillaries;
- by radiation between the walls of pores and capillaries;
- by convective heat transfer due to convective gas currents in the porous structure.

Previous factors together with the density of the material (since it affects the size of the gas structure elements, e.g., the pores) and the operating temperature determine the effective thermal conductivity of the material (2).

During the operation of fibrous thermal insulation materials under high temperatures, the synthetic binder used to bond the material fibres can be destroyed. The destruction of the binder affects the material density. The pore sizes increase, and the number of through pores increases, contributing to the intensification of convective heat transfer.

For the determination of thermal stability of studied objects and quantification of polymer binder content under various operating conditions, thermogravimetry with gas FTIR was used. As an operating instrument TG209F1 Libra (Netzsch GmbH, Selb, Germany), coupled with Alpha FTIR spectroscopic attachments (Bruker GmbH, Birriika, MA, USA) were applied. Analysis method complies with ASTM E2105-00. The thermogravimetric instrument was calibrated in an oxidising atmosphere (air) according to the c-DTA (pseudo-DTA) signal using the manufacturer's procedure for five high-purity calibration metals-InBi (alloy), In, Sn, Al, and Au for the interval of 30–1100 °C at 10K/min in an open alumina crucible (85 µL). The FTIR spectrometer is equipped with a DLaTGS detector, the gas cell windows are made of ZnSe with an antireflection coating, and absorbance mode was used. The sensitivity of the detector was checked via $Zn(C_{18}H_{35}O_2)_2$. The temperature of the spectrometer chamber was maintained at 200 °C, the temperature of the transit line was 190 °C. The range of recorded frequencies is 650–4400 cm^{-1} , the resolutions of spectra are 4 cm^{-1} and the number of scans is 16. Profiles of individual gases were plotted for CO₂,

CO and water vapor according to their individual frequencies in obtained spectra. Sample masses were from 9.7 to 16.2 mg.

Thermogravimetry analyser parameters were: temperature linearity—0.1 K; resolution—0.1 μg ; maximum mass—2 g. Balance accuracy was checked via certified $\text{CaC}_2\text{O}_4 \times \text{H}_2\text{O}$ according to the decomposition zones (3 runs) by mass scale and residual mass after instrument inner self balance calibration procedure (EMBcal). TGA (209F1) dynamic drift was also checked via empty alumina crucible, the meaning value by 3 repeats was 0.008 mg. For analysis of studied samples reproducibility were from $\pm 0.15\%$ to 0.28% within all mass loss ranges.

4. Results

4.1. Thermal Conductivity in Fibrous Thermal Insulation Materials for Cylindrical Samples

The thermal insulation cylinders made of basalt fibre from various manufacturers were used as samples. Their densities were 60, 80, 100, 120, and 150 kg/m^3 . For each sample, a series of experiments were carried out, during which the temperature on the outer surface of the metal pipe was maintained at 50, 100, 150, and 200 $^{\circ}\text{C}$ (the average temperatures of the thermal insulation layer, while the temperature on the insulated surface was maintained in the range from 50 to 350 $^{\circ}\text{C}$). Figure 2 shows the thermal conductivity of the samples of basalt fibre as a function of density and temperature. The presented results show that the thermal conductivity of fibrous thermal insulation materials is influenced by the operating temperature of the material and its density. With a decrease in the density of the material, the number of air inclusions, the size, and number of through pores increases, which leads to the intensification of convective heat transfer due to convective gas currents in the porous structure of the thermal insulation. On the other hand, with an increase in the material density, the mass of the heat-conducting mineral components increases, which leads to an increase in the conductive thermal conductivity.

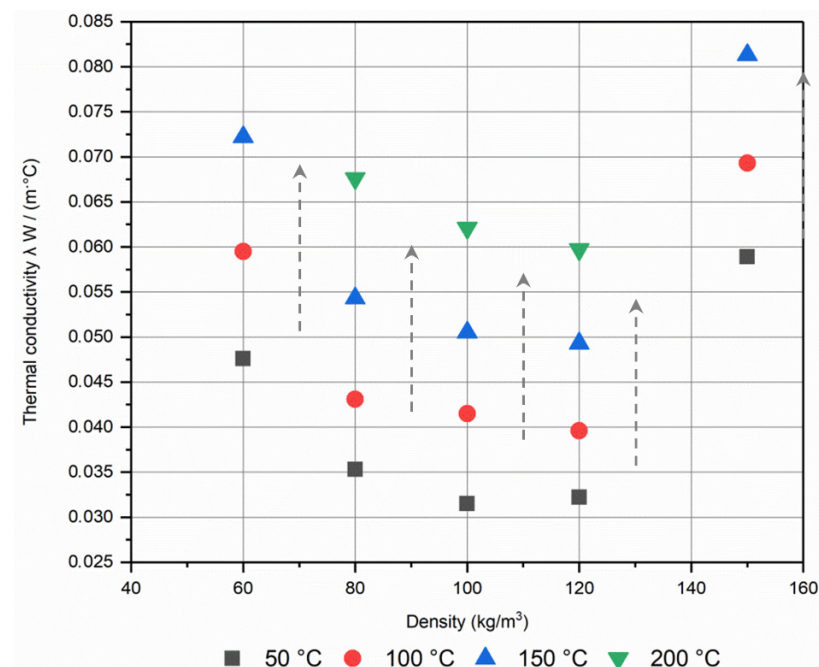


Figure 2. The thermal conductivity of the thermal insulation material made of basalt fibre as a function of density and the average temperature of the thermal insulation layer (50, 100, 150, and 200 $^{\circ}\text{C}$).

4.2. Influence of Temperature Modes of Operation on the Stability of the Heat-Shielding Properties

To determine the change in the thermophysical properties of thermal insulation during operation, samples of thermal insulation from basalt fibre were tested using the experimental setup shown in Figure 1.

The following samples were tested: sample No. 1 is the used basalt fibre, with dimensions of 400×400 mm and a thickness of 50 mm (Figure 3a). A sample of insulation was taken from a pipeline transporting superheated steam with a temperature of 315°C . Sample No. 2 is the new basalt fibre with dimensions of 400×400 mm and a thickness of 50 mm (Figure 3b).



Figure 3. The studied samples of basalt fibre: (a) used; (b) new.

The change in the coefficient of thermal conductivity, which underwent thermal destruction during operation at high temperatures, was determined. The thermal conductivity of sample No. 1 was $0.073 \text{ W}/(\text{m}\cdot^\circ\text{C})$ and the thermal conductivity of sample No. 2 was $0.037 \text{ W}/(\text{m}\cdot^\circ\text{C})$. The results indicate a deterioration in the heat-shielding properties of the material during long-term operation at high temperatures.

4.3. The Results of Thermogravimetric Analysis

For the thermogravimetric analysis the following samples were tested: (1) insulation sample No. 1 (used) was taken from a pipeline transporting superheated steam with a temperature of 315°C . The sample weight was 12.1 mg; (2) insulation sample of No. 2 (new) was basalt fibre and had a weight of 16.2 mg; (3) sample No. 3 was basalt fibre with a density of $80 \text{ kg}/\text{m}^3$, and a weight of 9.7 mg. Basalt thin fibre (BTF) has an elementary fibre thickness of 5 to $15 \mu\text{m}$ and a length of up to 50 mm. Various binders are used to bond the fibres, in an amount from 2 to 10%; (4) sample No. 4 was superfine basalt fibre (SFBF) and had a weight of 10.6 mg. SFBF is a super-thin basalt fibre, for which the thickness of the elementary fibre is 1–3 microns, and the length is more than 50 mm. STBF is produced without binders.

The heating rate of all samples was $10^\circ\text{C}/\text{min}$. The heating range was from 30°C to 1100°C . The experiment was carried out as follows: the high-precision balance determines the current weight of the sample at the set temperature and transfers the data to the PC. The differential thermogravimetric (DTG) curve characterises the rate at which weight changes with temperature. The results of the thermogravimetric analysis are shown in Figure 4. Sample No. 4 shows insignificant fluctuations in mass during heating, which can be attributed to the absence of binders in the material (STBF). Sample No. 3 of basalt thin fibre (BTF) showed a weight decrease of 3.61%, which can be associated with burnout (destruction) of the synthetic binder used to bond the fibres. That is why BTF is more susceptible to structural changes, in contrast to STBF.

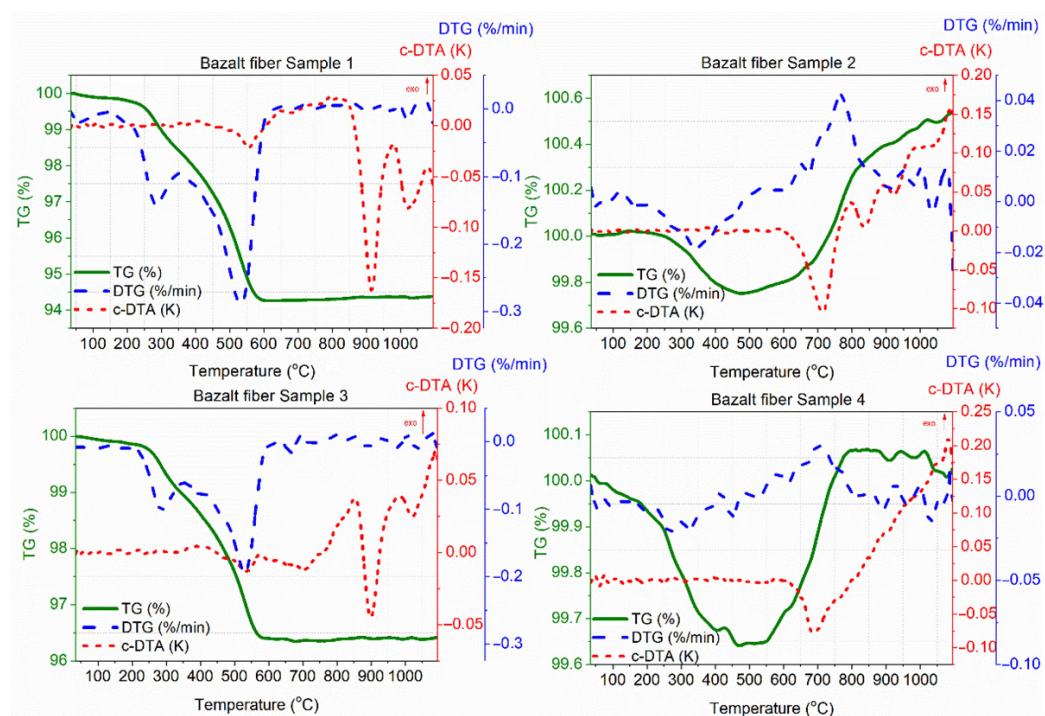


Figure 4. The results of thermogravimetric analysis of samples Nos. 1–4.

The decrease in weight in sample No. 1 was 5.74%. In this case, the decrease in mass (peak on the DTG curve) begins at 52.8 °C. At a temperature of 285.7 °C, the weight reduction was already 1.48%. This weight loss can also be attributed to the burnout of the binder at high temperatures. A change in the mass of fibrous thermal insulation materials caused by the burnout of the binder leads to an increase in the size of pores and capillaries, and hence to an intensification of convective heat transfer.

Obtained thermochemical parameters are presented in Figure 5 and Table 1. According to the results on the basis of TG-IR-Fourier experiments for new samples of basalt fiber-1 and 3, decomposition reactions are observed in identical temperature ranges. According to achieved IR-Fourier spectra, from RT (room temperature) to 300 °C, the processes of evaporation of crystallisation water are observed, after reaching 300 °C, the process of burnout of the polymer binder is observed, this fact is confirmed by the release of CO and CO₂ gases in IR-Fourier. After reaching 60 °C, according to the c-DTA results, endothermic processes are observed, probably associated with the melting of the minerals included in the fiber structure.

For fibre samples that were in operation (Nos. 2 and 4) for TG-IR-Fourier from room temperature to 500 °C, a slight decrease in weight (from 0.2 to 0.4%) is observed, probably associated with the evaporation of a minimum amount of absorbed organic compounds from the environment. After reaching 500 °C, an increase in the mass of the sample probably connected with processes of decomposition of the carbonate matrix and additional oxidation of oxides on the surface of the mineral fibre, which are overlapping on each other according to the results of IR-Fourier by CO₂ release.

A series of experiments was performed for three materials of different densities from the same manufacturer. The thermal conductivity of factory heat-insulating cylinders with densities of 80, 100, and 120 kg/m³ was determined in accordance with the requirements of GOST 32025-2012 (ISO 8497:1996). For each density, measurements were performed on three samples. The length of the samples was 500 mm, the insulation thickness was 17 mm, and the inner diameter of the cylinder was 32 mm. The temperature dependence of the thermal conductivity for materials with the smallest density is shown in Figure 6.

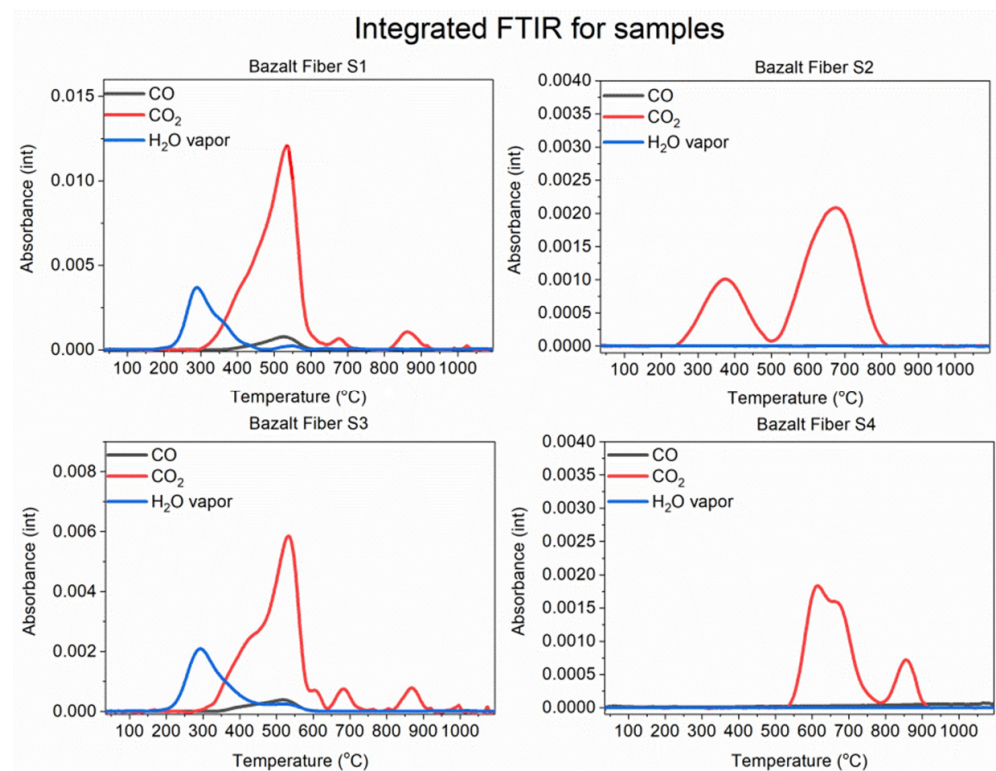


Figure 5. Integrated individual gases profiles for Basalt fibres 1–4 in an oxidising atmosphere.

Table 1. Main thermochemical parameters obtained in experiments.

New Basalt Sample No.	Δm_1 30–300 °C (%)	Δm_2 300–650 °C (%)	Δm_3 650–1000 °C (%)	DTG 1 (°C)	DTG 2 (°C)	DTG 3 (°C)
1	1.57	4.16	0.09	283.4	535.2	909.3
3	1.05	2.56	0.01	289.4	528.0	887.6
Used Basalt Sample No.	Δm_1 30–500 °C (%)	Δm_2 500–800 °C (%)	Δm_3 900–1000 °C (%)	DTG 1 (°C)	DTG 2 (°C)	DTG 3 (°C)
2	0.24	+0.51	+0.22	339.7	758.7	979.4
4	0.35	+0.42	0.01	272.0	696.3	1032.6

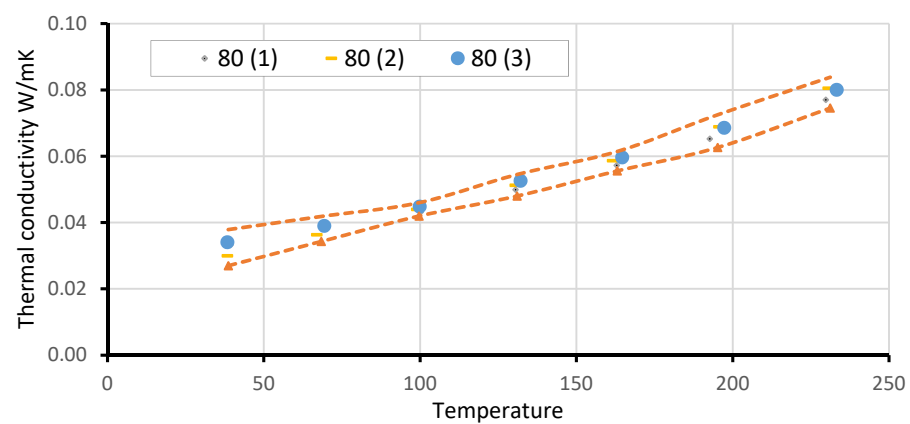


Figure 6. Dependence of the thermal conductivity coefficient ($W/m^{\circ}C$) from the temperature ($^{\circ}C$) for three samples with a density of 80 kg/m^3 .

The results obtained show the dependence of the thermal conductivity coefficient on temperature, as well as on the density of the material. These results are presented in

Table 2. Figure 7 also shows that with increasing temperature, the influence of density on the coefficient of thermal conductivity increases.

Table 2. Values of the thermal conductivity coefficient for materials with densities of 80, 100, and 120 kg/m³ for insulated surface temperatures in the range from 50 to 400 °C.

Temperature of the Insulated Pipe, °C	Average Temperature of the Insulation °C			Coefficient of Thermal Conductivity W/(m°C)		
	Density of 80 kg/m ³	Density of 100 kg/m ³	Density of 120 kg/m ³	Density of 80 kg/m ³	Density of 100 kg/m ³	Density of 120 kg/m ³
50	39	39	38	0.0324	0.0289	0.0299
100	68	69	68	0.0381	0.0359	0.0345
150	100	99	98	0.0440	0.0417	0.0396
200	131	129	128	0.0512	0.0476	0.0453
250	163	161	159	0.0585	0.0535	0.0507
300	195	193	191	0.0676	0.0626	0.0570
350	231	229	223	0.0792	0.0720	0.0651
400	-	261	257	-	0.0824	0.0741

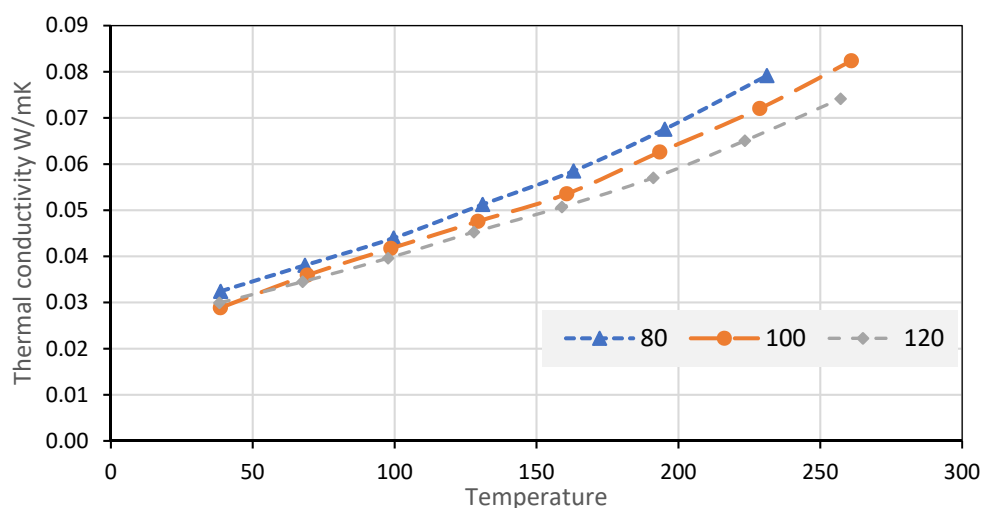


Figure 7. Dependence of the thermal conductivity coefficient (W/m°C) from the temperature (°C) for materials with densities of 80, 100, and 120 kg/m³.

Table 2 shows that for samples with a density of 80 kg/m³, the thermal conductivity coefficient was not determined. For these samples, at a temperature of 400 °C on the surface of the insulated pipe, the heat flux density recorded by the heat flux sensors exceeded the permissible measurement range 10 of 1000 W/m², and the temperature on the outer surface of the insulation reached values of more than 140 °C, which also exceeds the required operating temperature of the sensors.

5. Conclusions

The obtained results expand the available information on the dependence of the thermal conductivity of fibrous thermal insulation materials on density and temperature. They provide the accumulation of experimental data for practical use and test new theoretical ideas about the nature of heat transfer processes in fibrous insulating materials.

The dependence of the thermal conductivity of fibrous thermal insulation materials on the temperature of the insulated surface (in the range from 50 °C to 500 °C), and on the density of the thermal insulation material was obtained. The effect of high temperatures on the change in the mass of fibrous thermal insulation materials associated with the burnout

of synthetic binders is shown. However, a more detailed study is hampered by the lack of data on the composition of the binders used, which is a commercial secret of manufacturers. Taking these features into account in the design of thermal insulation operating at high temperatures will make it possible to choose thermal insulation materials with optimal properties that ensure the magnitude of heat losses within the standard values, as well as the stability of the heat-shielding properties during operation. Thus, the thermal insulation made of mineral wool has a high chemical resistance. The material is chemically inert and does not cause corrosion during prolonged contact with metals; therefore, it is widely used for thermal insulation of high-temperature equipment and steam networks.

Author Contributions: Conceptualisation, A.F., I.A. and U.B.; formal analysis, A.F., O.A. and I.A.; investigation, Y.V., E.B., D.E. and A.F.; project administration, I.A. and U.B.; visualisation, E.B. and O.A.; writing—original draft, Y.V., D.E., A.F. and U.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Ministry of Science and Higher Education of the Russian Federation within the framework of the state assignment No. 075-01262-22-01 from 28 January 2022 (Additional agreement 075-03-2022-151/1 from 31 January 2022).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Apkaryan, A.S.; Kulkov, S.N. Study of the Thermophysical Properties of a Glass-Ceramic Material for Thermal Insulation of Pipelines of Heating Pipe Mains and Utilities. *Inorg. Mater. Appl. Res.* **2021**, *12*, 499–503. [\[CrossRef\]](#)
2. Apkaryan, A.S.; Kulkov, S.N. Formation of structure and closed porosity under high-temperature firing of granules of porous glass-ceramic material. *Inorg. Mater. Appl. Res.* **2018**, *9*, 286–290. [\[CrossRef\]](#)
3. Mozgova, A. Testing heat supply networks for heat losses. *E3S Web Conf.* **2021**, *274*, 08003. [\[CrossRef\]](#)
4. Karabekova, D.Z.; Kissabekova, P.A.; Nussupbekov, B.R.; Khassenov, A.K. Analysis of the insulation state of underground pipelines in the heating network thermal engineering. *Therm. Eng.* **2021**, *68*, 802. [\[CrossRef\]](#)
5. Lidén, P.; Adl-Zarrabi, B.; Hagentoft, C.E. Diagnostic protocol for thermal performance of district heating pipes in operation. Part 2: Estimation of present thermal conductivity in aged pipe insulation. *Energies* **2021**, *14*, 5302. [\[CrossRef\]](#)
6. Berge, A.; Adl-Zarrabi, B.; Hagentoft, C.E. Assessing the thermal performance of district heating twin pipes with vacuum insulation panels. *Energy Procedia* **2015**, *78*, 382–387. [\[CrossRef\]](#)
7. Park, J.W.; Lim, O.K.; You, W.J. Analysis on the fire growth rate index considering of scale factor, volume fraction, and ignition heat source for polyethylene foam pipe insulation. *Energies* **2020**, *13*, 3644. [\[CrossRef\]](#)
8. Krawczyk, D.A.; Teleszewski, T.J. Reduction of heat losses in a pre-insulated network located in central Poland by lowering the operating temperature of the water and the use of egg-shaped thermal insulation: A case study. *Energies* **2019**, *12*, 2104. [\[CrossRef\]](#)
9. Teleszewski, T.J.; Krawczyk, D.A.; Roderio, A. Reduction of heat losses using quadruple heating pre-insulated networks: A case study. *Energies* **2019**, *12*, 4699. [\[CrossRef\]](#)
10. Ministry of Economic Development of the Russian Federation. State Report on the State of Energy Conservation and Energy Efficiency in the Russian Federation. Available online: <https://www.economy.gov.ru/> (accessed on 17 February 2022).
11. *Fuel and Energy Complex and Economy of Russian Regions. Directory*; Publishing House Energiya: Moscow, Russia, 2007; Volume 4.
12. Guryev, V.V.; Zholudov, V.S.; Petrov-Denisov, V.G. *Thermal Insulation in Industry. Theory and Calculation*; Stroyizdat: Moscow, Russia, 2003; p. 416.
13. Order of the Ministry of Energy of the Russian Federation of 30 December 2008 No. 325 “On Approval of the Procedure for Determining the Standards for Technological Losses during the Transfer of Heat Energy, Heat Carrier”; Ministry of Energy: Moscow, Russia, 2008. Available online: <https://minenergo.gov.ru/> (accessed on 17 February 2022).
14. Zhao, J.-F.; Qiao, L.-B.; Yang, H.-L.; Zhang, L.; Yu, Z.-T. Experimental study on characteristics of thermal and pipeline loss of steam heating pipeline network. *Zhejiang Daxue Xuebao (Gongxue Ban)/J. Zhejiang Univ. (Eng. Sci.)* **2021**, *55*, 1135–1141.
15. Elagina, O.Y.; Ageeva, V.N.; Buklakov, A.G. Some aspects of heat-insulating materials application on systems of oil fields steam pipelines. *Neftyanoe Khozyaystvo-Oil Ind.* **2019**, *10*, 87–89. [\[CrossRef\]](#)
16. Berardi, U. The impact of aging and environmental conditions on the effective thermal conductivity of several foam materials. *Energy* **2019**, *182*, 777–794. [\[CrossRef\]](#)

17. Berardi, U.; Naldi, M. The impact of the temperature dependent thermal conductivity of insulating materials on the effective building envelope performance. *Energy Build.* **2017**, *144*, 262–275. [CrossRef]
18. Berardi, U.; Nikafkar, M.; Wi, S.; Kim, S. Experimental verification of the theoretical aging of vacuum insulated panels. *J. Ind. Eng. Chem.* **2020**, *90*, 300–304. [CrossRef]
19. Li, A.V. Durability of Energy-Efficient Polymer-Containing Enclosing Structures: Thesis for the Degree of Cand. of Tech. Sciences. Ph.D. Thesis, Far Eastern State Technical University, Khabarovsk, Russia, 2003.
20. Ivantsov, A.I. Prediction of the Service Life of the Outer Walls of Residential Buildings Based on the Loss of the Required Thermal Protection: Thesis for the Degree of Cand. of Tech. Sciences. Ph.D. Thesis, Kazan State University of Architecture and Civil Engineering, Kazan, Russia, 2014.
21. Bobrov, Y.L. *Durability of Thermal Insulation Mineral Wool Materials*; Stroyizdat: Moscow, Russia, 1987.
22. Pavlov, M.; Karpov, D.; Akhmetova, I.; Monarkin, N. Assessment of energy efficiency of application heat-insulating paint for the needs of district heat supply systems. *E3S Web Conf.* **2020**, *178*, 01004. [CrossRef]
23. Behi, H.; Behi, M.; Ghanbarpour, A.; Karimi, D.; Azad, A.; Ghanbarpour, M.; Behnia, M. Enhancement of the Thermal Energy Storage Using Heat-Pipe-Assisted Phase Change Material. *Energies* **2021**, *14*, 6176. [CrossRef]
24. Zholudov, V.S. Improving the Heat-Shielding Properties of Heat-Insulating Structures Made of Fibrous Materials for Industrial Structures: Thesis for the Degree of Cand. of Tech. Sciences. Ph.D. Thesis, Russian State Open Technical University of Railways, Moscow, Russia, 2000.
25. The Russian State Standard GOST 32025-2012. Thermal Insulation. Method for Determining the Characteristics of Heat Transfer in Factory-Made Cylinders in a Stationary Thermal Regime. Available online: <https://docs.cntd.ru/document/1200101975> (accessed on 17 February 2022).
26. Bazukova, E.; Vankov, Y. Increasing the reliability of thermal energy transportation systems taking into account forecasting the properties of thermal insulation during operation. *E3S Web Conf.* **2020**, *216*, 01078. [CrossRef]
27. Bazukova, E.R.; Vankov, Y.; Gaponenko, S.O.; Smirnov, N.N. Investigation of the thermal conductivity coefficient of basalt fiber insulation at various temperature conditions. *ISEU Bull.* **2021**, *4*, 15.
28. The Russian State Standard GOST 7076-99; Building Materials and Products. Method for Determination of Thermal Conductivity and Thermal Resistance under Stationary Thermal Conditions. Gosstroy of Russia, GUP TsPP: Moscow, Russia, 2000. Available online: <https://docs.cntd.ru/document/1200005006> (accessed on 17 February 2022).
29. Saifullin, E.R.; Vankov, Y.V.; Bazukova, E.R.; Maryashev, A.V. Evaluation of heat transporting losses due to changes of insulation properties during operation. *J. Phys. Conf. Ser.* **2018**, *1058*, 012061. [CrossRef]