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Determination of thermal conductivity of baled agricultural biomass

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ABSTRACT

Modeling of transport phenomena in materials with porous bed features requires thermophysical properties, such as porosity, permeability and thermal conductivity be known.

The paper presents experimental data obtained in the course of investigation focused on analysis of stagnant thermal conductivity of biomass. Experiments were conducted using a custom designed and constructed experimental setup and implementing original experimental procedure. Results obtained enabled stagnant thermal conductivity of biomass to be determined for different biomass porosity values.

Analysis of the experimental data enabled functional dependence of stagnant thermal conductivity on porosity to be determined, with porosity varied in a range 0.50–0.85. Results obtained indicate that reduced bed porosity, down to the value of 0.65, causes stagnant thermal conductivity of the bed to be reduced. Further porosity reduction, below the value of 0.65, results in increased stagnant thermal conductivity of the bed.

Experimental procedure developed shall be useful for gathering experimental data on different materials planned to be analyzed when examining transport phenomena occurring during combustion of biomass bales. In addition, data to be acquired shall be helpful in modeling the transport phenomena associated with combustion in porous beds.

1. Introduction

In terms of sustainable energy development there is a growing need for using the renewable energy sources. A need for the utilization of this kind of energy sources is dictated by the market, on one side, as well as by environmental protection, on the other. With regard to sustainable energy resources, it is necessary to meet conditions defined by EU in order to reduce the environmental pollution and greenhouse gas emissions as well as to encourage innovation in this area.

Technically utilizable energy potential of the renewable energy sources in the Republic of Serbia is very significant and is estimated at around 6 million tons of oil equivalent per annum-of which 3.3 Mtoe is in the production of biomass, 1.7 Mtoe is the potential of hydro-power, 0.2 Mtoe is geothermal, 0.2 Mtoe is wind power and 0.6 Mtoe is solar energy.

The most significant renewable energy source is biomass, which can be used in several ways. Some of these ways are gasification and pyrolysis that are the process of conversion of solid fuel to gas [1,2], which is easier to be used in power production.

Biomass can be used in existing and new installations combined with another type of fuel so-called co-combustion [3]. This type of energy generation from biomass is most often used in the existing TPP's combined with coal as the primary fuel. Problems occurring are bound mainly with the problem of creating deposits at heat exchange surfaces.

The most efficient way of using biomass in power production is combustion [4]. Combustion can be performed in many ways. In principle, these combustion technologies are the most commonly used ones:

- grid type combustion,
- fluidized bed combustion,
- pulverized coal combustion.

What technology will be used depends mainly upon physico-chemical characteristics of the biomass. The fact that the most efficient way is using biomass in its original form, so that the energy needed for its preparation for combustion is minimal should be taken into account.

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Nomenclature

Latin symbols:

d	diameter, [m]
l	cylinder height [m]
Pr	Prandtl number, [Dimensionless]
Q	heat transfer, [W]
T	temperature, [°C]
SD	standard deviation, [%]
U	measurement uncertainty, [%]

Greek letters

ε	porosity, [Dimensionless]
λ	thermal conductivity, [W/(m K)]

Index

eff	effective
dis	dispersion
f	fluid
in	inner
o	stagnant
out	outer
s	solid
β	thermal expansion coefficient
ν	kinematic viscosity

One of the most popular ways for efficient use of biomass in combustion is the cigar combustion of baled biomass.

Combustion of biomass bales in cigar burners represents new and insufficiently explored technology [5,6]. The main feature of the considered process is the fact that combustion mainly occurs in the bale, which based upon its properties, is considered to be a porous bed [7–9]. Modeling of transport phenomena in porous bed requires thermophysical properties, such as porosity, permeability and thermal conductivity to be known. On the other hand, literature data provide scarce information on the parameters mentioned [7–10].

All porous media models can be divided into two main categories: capillary and spheroidal. The simplest porous media model represents a body containing same size cylindrical pores. The other model assumes that a body is containing monodisperse spherical particles [7–11]. However, porous bed of biomass bale has quite specific structure, preventing either one of the models to be considered fully appropriate. However, the model based on cylindrically shaped pores is deemed to be more suitable for the case examined.

In accordance with that model, porosity of the material is defined based on the assumption that a cavity is connected to other cavities via one or more pores (canals). There is also a case when a cavity is connected to only one pore or is not connected to other cavities at all. This means that there are certain parts in porous structure comprised of cavities with no fluid flowing inside them and other cavities that allow fluid flow (the so-called “transient” pores). According to Kaviany [12], fluid flow can be regarded either as a flow through tortuous pores, which is the assumption made in the capillary flow model, or a flow over a considered objects i.e. the friction model.

The friction model [12], which is predominantly used to describe heat transfer phenomena in porous media, assumes that heat conducted through the media is transferred either in series or in parallel fashion both through solid and the gas phase. This effect is more pronounced when there is a gas flow inside the pores of porous media. The friction model, basically, defines total effective thermal conductivity (λ_{eff}) that takes into account all previously mentioned heat transfer mechanisms (conduction and convection) while assuming that heat is transferred trough the porous media by conduction only [11–13].

The said thermophysical property is highly complex and generally depends on numerous parameters such as: geometry of porous media (porosity, number of pores, shape of pores, pore curvature, the percentage of closed pores etc.), thermal conductivity of solid and gas phase, hydrodynamic properties of gas phase (velocity, temperature and pressure), flow characteristics (laminar vs. turbulent flow) etc. Assuming that combustion of biomass bales results in laminar flow [11–13], effective thermal conductivity can be divided into stagnant (λ_o) and dispersion (λ_{dis}) thermal conductivity terms:

$$\lambda_{eff}=\lambda_o+\lambda_{dis} \tag{1}$$

Dispersion thermal conductivity takes into account phenomena that occur in porous media as a result of gas flow inside the pores, caused by external factors [11,12].

In case when there is no gas flow, stagnant thermal conductivity is equal to effective thermal conductivity of porous media. In such case, conductivity is quantitatively and qualitatively affected by the following properties of porous media: porosity (ε), solid phase thermal conductivity (λ_s) and gas phase thermal conductivity (λ_f), as well as distribution of pore and solid matrix with respect to heat flow direction (temperature gradient). If it is assumed that heat transfer through the porous media is achieved by simultaneous heat conduction both through pores and the solid matter, stagnant thermal conductivity can be expressed as [11]:

$$\lambda_o=(1-\varepsilon)\cdot\lambda_s+\varepsilon\cdot\lambda_f \tag{2}$$

Anotherpossible matrix orientation is based on the assumption that pore and solid matter are distributed so as to alternate in a series-like manner in the heat flow direction. In such case, stagnant thermal conductivity can be expressed as follows [11]:

$$1/\lambda_o=(1-\varepsilon)/\lambda_s+\varepsilon/\lambda_f \tag{3}$$

By combining Eqs. (2) and (3) and using a simple mathematical analysis, it is concluded that stagnant thermal conductivity, under the assumption of parallel heat transfer mode, is always bigger than solid phase thermal conductivity, except in case when λ_s is greater than λ_f.

For practical applications described in the literature [11], another correlation between λ_s and λ_f is proposed to be used when defining stagnant thermal conductivity:

$$\lambda_o=\lambda_s^{1-\varepsilon}\cdot\lambda_f^{\varepsilon} \tag{4}$$

This correlation, however, does not provide satisfactory results when the difference between λ_s and λ_f is particularly large (several orders of magnitude). Applicability of the expression is conditioned not only upon the known λ_s and λ_f values, but also upon the known and preferably regular geometry of the porous media. Namely, in case of fibrous porous media, if heat is transferred along the longitudinal axis of the fiber, it is correct to use serial correlation for stagnant heat transfer coefficient. In other case, when heat is transferred laterally with respect to the fiber axis, harmonic correlation is to be used.

Besides the outlined models there are other, more complex models, as the Maxwell–Eucken model and Effective Medium Theory (EMT) equation [14,15], that take into account complex way of packing the spherical shape pores. Fig. 1 illustrates the dependence $\lambda_{\mathrm{eff}}/\lambda_s$ of porosity obtained by using the mentioned models.

However, problems encountered in practice are commonly not so precisely defined, meaning that strict implementation of the above mentioned analysis, may cause incorrect data to be obtained. For the said reason, the most reliable way to obtain trustful data is to acquire them through experimental investigation of stagnant thermal conductivity. It is also important for experimental data to be based on the largest possible sample examined in order to maximally reduce the impact of anisotropic material features on the measurement error. Therefore, experimental setup needs to be robust enough and cylindrical in shape so as to sustain all tensions and stress forces that come into effect during biomass compressing, performed in order to achieve porosity values required.

In practice there are 2 groups of stationery (steady state) methods for determining thermal conductivity, and these are axial and radial methods, which are applied depending on the structure of the sample. All the methods are based on measuring the temperature gradient in the sample, and the heat flux. Axial methods are the most widely used, give a satisfactory precision of measurement, and as the heat source flat plate is used, while in radial methods as the heat source a cylinder is used. Both type of methods give a satisfactory precision.

Guardede hot plate method is used for determining thermal conductivity of dielectrics as are glass, ceramics, polymers, insulation, with thermal conductivity below 1 W/(m K) [16]. This method is used in temperature range 80–800 K with measurement error of around 2%. Advantages of this method are great applicability and high precision, and drawbacks are long testing time, and testing only materials with low heat conductivity.

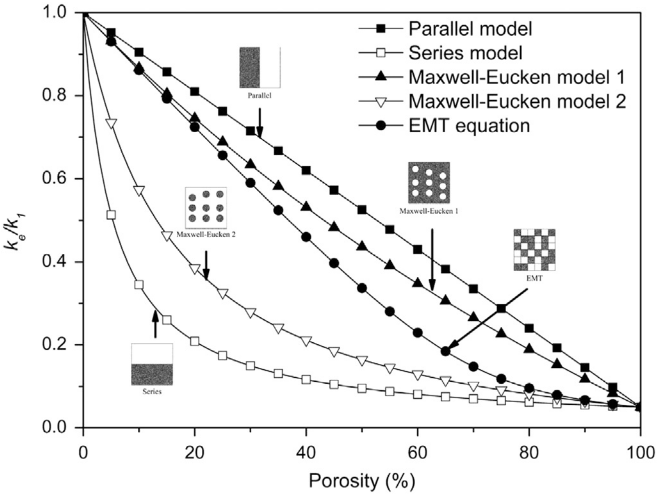

Fig. 1. Effective thermal conductivity by five basic models.

Axial heat flow method was developed long time ago and has high precision of determining heat conductivity. The method is widely used only for samples of fine structure in the range 10–500 W/(m K), at temperatures below 100 K. Its measurement error is about 0.5–2% [17].

Cylinder method belongs to the group of radial methods. The advantage of this method is a simple construction of installation. Therefore it is popular and spread widely [18]. It is used for materials with thermal conductivity in the range 0.01–200 W/(m K), in the wide range of temperatures at 4–1000 K. Precision of the method is given as measurement error of 2%.

Heat flow method is similar to the Guardede hot plate method, with difference that heater (plate) is replaced by heat fluxmeter. The method is used to determine heat conductivity of materials as polymers and insulators with thermal conductivity below 0.3 W/(m K) [19,20].

Overview of methods for determining heat conductivity of porous layer is given in Table 1.

Experimental method developed by Nozad [21] and later implemented by Dias [22], is based on determination of effective thermal conductivity of porous materials through measurement of heat flow and temperature gradient in the sample. Dias at al. [22] conducted experimental investigation in order to determine thermal conductivity of glass balls. Experiments were performed on a cylindrical sample and rested upon the assumption of axial heat transfer direction along the sample. In order to reduce radial heat transfer, experimental apparatus was provided with appropriate thermal insulation. Such approach is not suitable to be used in case of biomass bales due to wide range of porosity values that need to be examined, as well as the assumption that, in spite of thermally insulated outer wall of the apparatus used, considerable radial heat flow still occurs.

Experimental method developed by Ando [23] is based on similar principle. The author used similar method to determine thermal conductivity of metal foam, but under unsteady flow conditions which were achieved by blowing heated air through the porous sample. This method would also not be suitable for agricultural biomass sample since the hot medium would cause changes in composition and even in the mass of sample examined.

Krause [24] proposed a method for determining thermal conductivity of particulate matters based on the laser induced heating of cylindrically shaped sample and infrared recording of the resulting temperature profile. This method is also not suitable to be used for analysis of baled agricultural residues, mainly for the reasons similar to those mentioned previously [23].

C.C. Chueh et al. [25] analyzed influence of open and closed pores at thermal conductivity of isotropic porous medium. Tests were conducted in low range of porosity at 0–0.4 and the conclusion is that porous medium with open pores has somewhat lower heat conductivity than the porous medium with closed pores. In both cases the decrease of porosity results in an increase of the effective thermal conductivity. Narrow range of porosity (0–0.4), in

Table 1
Summary of the thermal conductivity measurement techniques.

Measurement method	Materials	Conductivity range (W/(m K))	Temperature range (K)	Uncertainty	References
Guarded hot plate	Glass, ceramics, polymers, insulation	<1	80–800	~2%	[16]
Axial heat flow	Small specimens with thermal conductivity > 10 W/(m K)	10–500	<100	0.5–2%	[17]
Cylinder method	Wide applications due to simple construction	0.01–200	4–1000	~2%	[18]
Heat flow method	Polymers and insulation materials with thermal conductivity <0.3 W/(m K)	<5	200–500	3–10%	[19,20]

which tests were performed in this work, is the limiting factor for application of the obtained results to the case of baled biomass.

Table 2 presents a review of past work on experimental determining heat conductivity of porous layer.

Overview of available literature data leads to conclusion that not much research has been done in order to examine phenomena addressed. This implies that custom developed experimental procedure, providing data to be used for process modeling, would need to be conducted if reliable data are to be gathered. Besides, size and structure of biomass bales made of agricultural residues represent another reason why larger volume samples need to be used in experiments performed. Analysis of commercially available installations commonly utilized to determine thermal conductivity of different materials has indicated that known devices are not suitable to be used for analysis of oilseed rape bales, which were the main focus of experimental investigation presented herein. This is mainly because volume of the sample deemed representative of heat transfer phenomena occurring in the bale, would significantly exceed working volume of any of the commercial installations. It is for that reason that custom developed experimental procedure and specially designed and constructed experimental apparatus were used to investigate stagnant thermal conductivity of biomass bales.

Basic equation used when determining stagnant thermal conductivity is the *Fourier Law* related equation which states that the amount of heat transferred through a medium is proportional to the temperature gradient in the medium. For a cylindrical wall, this can be expressed as follows:

$$\lambda_o = |\dot{Q}|/(2\pi l \Delta T)\ln(d_2/d_1) \tag{5}$$

Where d_2 and d_1 are the outside and the inside cylinder diameters respectively, $\dot{Q}$ is the total amount of heat transferred through the sample and l is the length of the cylinder. In this manner, by measuring temperature difference between inner and outer cylinder walls, as well as the amount of the heat transferred between these two said walls, the related heat transfer coefficient is easily determined.

2. Experimental investigation and measurement error

Experimental investigation outlined in this work was performed with the aim to determine stagnant thermal conductivity of baled agricultural residues, as well as to examine its dependence on several combustion parameters. Measurements performed were expected to provide better understanding of transport phenomena occurring in the porous bed formed by biomass bales made of agricultural residues. Experimental data were also intended to be used in combustion process modeling.

Experiments were performed in a custom-made experimental apparatus, designed in such manner so as to simulate, as much as possible, real conditions occurring during combustion of bales made of agricultural residues in semi-industrial facility equipped with cigar burners [6–9].

Having in mind that agricultural biomass has anisotropic features, representative sample needed to be as large as possible so as to maximally reduce the impact of anisotropic properties, as mentioned earlier herein above.

Experimental setup (Fig. 2) was designed and constructed so as to be suitable for determination of stagnant thermal conductivity, enabling λ_o to be defined for the range of porosity values that commonly occur in combustion process under real conditions [7–9].

Experimental installation developed enabled porosity of a constant mass biomass sample to be varied in preselected range by changing the volume of working unit (Item no. 4) in the apparatus constructed. Working unit of the apparatus is large enough to accommodate 1 kg of biomass sample in its free form, which was deemed sufficient to reduce impact of anisotropic biomass features on the measurement results.

Working unit of the apparatus constructed, indicated as Item no. 4, enables desired porosity of the oilseed rape sample to be achieved. This is accomplished by compressing the sample, placed between a top (Item no. 1) and a bottom (Item no. 2) plate, by the means of screws (Item no. 5). Central cylinder (item no. 6) acts as a heat source in the setup. Inner cylinder is positioned on the supporting plate (Item no. 2). The heat source is equipped with electric heater (Item no. 8) of adjustable power output. Heat is transferred from the central cylinder to the annular cylinder (Item No. 4). Surface wall temperatures of inner and annular cylinder are measured in points indicated as Items no. 7 and no. 9 respectively. A conical end portion of the inner cylinder enables easier biomass compression. A thermal insulation layer is provided between the top plate and the working cylinder in order to prevent thermal bridge to be formed between the said two components. In this manner, heat conducted from the inner and to the outer cylinder through the top plate is minimized. Connection between the working cylinder and the bottom plate is preferably achieved through a single-point of contact, since the case in question involves two spherical shapes of different diameters (i.e. 199 mm diameter bottom plate and 205 mm diameter working cylinder). In this manner, heat transfer to the bottom plate is also maximally reduced. Based on the description provided, it is concluded that heat transfer between the inner and the outer cylinder is mostly achieved by heat conduction through the biomass sample.

Temperature measurement openings and position of related thermocouples are shown in Fig. 2. In order to be able to analyze uniform temperature distribution along the perimeter of both inner and outer cylinder, an opening is provided on the opposite side of each cylinder in locations where temperature measurements were deemed to be the most important with respect to stagnant thermal conductivity values.

Experimental installation used in stagnant thermal conductivity measurements is presented in Fig. 3. As it was mentioned earlier, thermal conductivity measurements were based on the measurement of surface temperatures of outer and inner cylinder, as well as measurement of ambient temperature required for determining heat transfer rate from the outer cylinder. This amount of heat also represents the amount of heat transferred

Table 2
Summary of previous work.

Sl. no.	Author(s)	Measurement techniques	Parameters studied
1.	Ando et al. (2013) [23]	Axial heat flow	Heat transfer coefficients of ceramic foams in forced convective flows
2.	Krause et al. (2011) [24]	Cylinder method	Heat transfer coefficients of fragile and sensitive materials with non-invasive technique
3.	Dias et al. (2007) [22] Nozad et al. (1985) [21]	Axial heat flow	Heat transfer coefficients of glass balls
4.	Chueh et al. (2014) [25]		Impact of open and closed pore size of the thermal conductivity of an isotropic porous medium
5.	Asakuma and Yamamoto (2013) [28]		The effect of porosity on thermal conductivity with the stochastic arrangement of pores

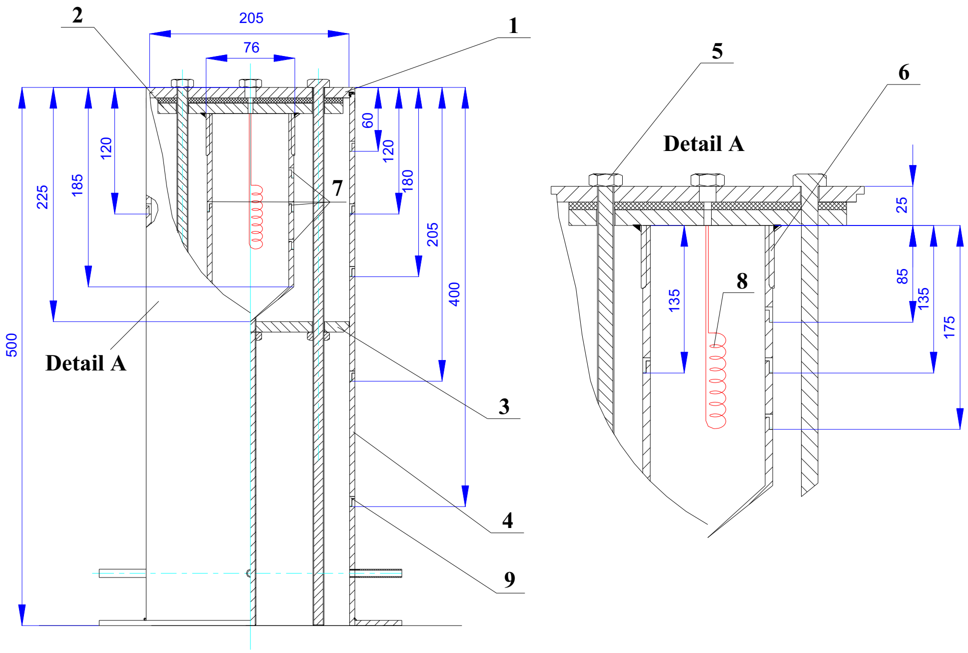

Fig. 2. Experimental installation used in thermal conductivity measurements. 1- Top plate, 2- Inner cylinder supporting plate, 3- Bottom plate, 4- Working cylinder, 5- Biomass compressing screw, 6- Inner cylinder, 7- Openings for the inner cylinder thermocouples, 8– Heater and 9- Openings for the outer cylinder.

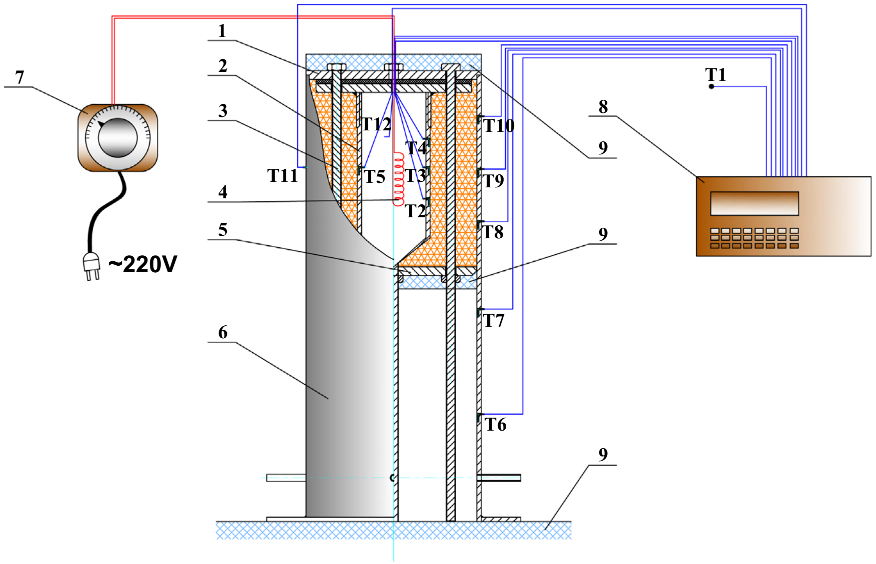

Fig. 3. Experimental installation used in stagnant thermal conductivity measurements. 1- Top plate, 2- Inner cylinder, 3- Compressing screw, 4– Heater, 5- Bottom plate, 6- Outer cylinder, 7- Voltage regulator, 8- Acquisition system and 9- Thermal insulation.

through the biomass bed. Temperatures were measured using the thermocouples (T1–T12). Data were acquired via data acquisition system (Item no. 8). In order to maximally reduce heat losses, experimental installation was thermally insulated by a Styropor® layer (Item no. 9). Data obtained by measurement of the surface temperatures of insulated elements showed that the measured temperatures are the same as ambient temperature, thereby pointing out that no heat is being transferred through the insulated elements. Temperature of inner cylinder, which was not allowed to exceed 100 °C, was controlled by a voltage regulator (Item no. 7).

Heat transfer rate defined by Eq. (6) represents the amount of heat transferred from the outer wall of the cylinder to the surrounding environment. Outer cylinder temperature was determined as the weighted average of measured temperature data, using the weighting factors attributed to the surface whose temperature was measured.

As seen in Fig. 2, the inner cylinder is not entirely cylindrical in shape, but comprises a cone-shaped ending. For this reason, length of the inner cylinder needed to be adjusted by adding together the length of the inner cylinder, excluding the cone ending, and a length of hypothetical cylinder whose surface area equals that of the cone. In that manner, length of the inner cylinder, used in Eq. (6), was determined to be $l = 0.1818$ m. Other characteristic dimensions are shown in Fig. 2.

Stagnant thermal conductivity was determined based on the heat transfer model that simulates heat transfer through cylindrical wall. Measurements of temperature difference between outer and inner cylinder walls provided input data for the model considered. In order to simplify procedure for determining stagnant

Table 3
Temperature data used for determining thermal conductivity.

Porosity	Temperature, [°C]											
	T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}	T_{11}	T_{12}
Styropor®	13.10	70.30	70.41	64.72	69.90	20.54	21.66	22.76	23.60	24.52	23.61	62.80
0.84	17.38	58.47	60.88	57.50	60.25	19.44	20.37	21.29	21.75	22.6	21.92	60.75
0.80	16.25	62.35	63.94	59.93	63.43	18.38	19.26	20.14	20.50	21.37	20.86	60.14
0.75	16.53	56.59	58.88	55.97	58.31	18.26	19.19	20.01	20.31	20.89	20.61	59.65
0.71	16.56	60.33	62.00	57.93	61.59	18.38	19.25	20.09	20.49	21.17	20.63	59.92
0.67	19.13	70.23	71.17	66.34	70.83	21.04	21.86	22.69	23.06	23.70	23.15	66.98
0.63	18.23	73.43	74.21	68.84	73.87	20.15	21.10	22.08	22.58	23.38	22.58	67.93
0.59	18.92	76.32	76.71	71.15	76.28	20.86	21.82	22.86	23.41	24.24	23.55	67.84
0.55	16.26	71.55	72.13	66.80	71.58	18.15	19.21	20.34	20.97	21.94	20.77	64.41
0.51	19.51	74.16	74.8	69.49	74.20	21.69	22.63	23.59	24.00	24.80	24.17	69.61

Table 4
Determination of stagnant thermal conductivity.

Porosity	*Nu* [Dimensionless]	α $\left[{}^{W}/_{(m^2K)}\right]$	$\lvert\dot{Q}\rvert$ [W]	λ $\left[{}^{W}/_{(mK)}\right]$	λ_{kor} $\left[{}^{W}/_{(mK)}\right]$
Styropor®	62.23571	3.149127	3.48936	0.060650	0.01565
0.84	62.30117	3.277041	3.816919	0.090495	0.07447
0.80	62.60178	3.292854	3.839044	0.081796	0.06578
0.75	60.20605	3.166838	3.170601	0.075692	0.05967
0.71	60.75434	3.195678	3.319538	0.074119	0.0581
0.67	60.30438	3.17201	3.333626	0.063932	0.04791
0.63	61.62075	3.241252	3.662114	0.065501	0.04948
0.59	61.81089	3.251253	3.760245	0.065007	0.04899
0.55	62.95606	3.311489	3.949901	0.071243	0.05522
0.51	62.32851	3.278479	3.958971	0.072021	0.056

thermal conductivity, assumptions were made that do not significantly affect accuracy of the results obtained. First assumption states that inner and outer wall surface temperatures are equal. This assumption was deemed justified due to the small wall thickness and thermal conductivity of the wall material (steel) which is several order of magnitude higher than thermal conductivity of examined material. In addition, it is assumed that wall temperature and temperature of the sample that is in direct contact with the wall are equal. By compressing the sample until reaching desired density i.e. sample porosity, sample material is pressed strongly against the walls of experimental apparatus. This provides good contact between examined material and the wall, thereby reducing thermal resistance and making it justified to assume that temperatures of the wall and the sample which is in direct contact with the wall are equal. The characteristic inner and outer sample surface temperatures were taken to be the mean inner and outer wall surface temperatures of the corresponding wall segments. Temperatures T_1–T_{12} were selected during steady state regime, achieved after approximately 24 h of operation.

Validation of experimental method described above was performed through measurement of thermal conductivity of porous media characterized by known thermal conductivity. For the said purpose, expanded polystyrene (hereinafter *Styropor*®) was used as a reference material, with known thermal conductivity of $\lambda = 0.045$ W/(m K). The specified thermal conductivity of selected reference material was chosen comparable to the expected thermal conductivity of baled agricultural residues.

Temperatures were measured using K-type thermocouples, with temperature data collected via data acquisition system. Measurement uncertainty associated with the entire temperature measurement set, which includes thermocouple and data acquisition system, equals 2.5%. Bearing in mind that surface temperatures measured on the inner and outer cylinder were averaged, total measurement error needed to include standard deviation which, in case of inner cylinder temperature measurement, equaled maximally 2.36%, while for the outer cylinder temperature measurement equaled maximally 1.51%. In addition, heat transfer coefficient indicative of the heat transfer rate from the outer cylinder wall to the ambient surroundings required five air-related parameters to be determined: Prandtl number for temperature distant from the wall, Prandtl number for wall temperature, thermal conductivity of air, thermal expansion coefficient and kinematic viscosity. Uncertainties associated with the thermocouple measurements were used to determine the measurement uncertainties for determination of indicated parameters: 0.015% for Prandtl numbers, 0.27% for thermal conductivity, 0.34% for thermal expansion coefficient and 0.6% for kinematic viscosity.

Based on expanded individual measurement uncertainties, calculated from accuracy classes of specific measurement chains, total expanded measurement uncertainty is defined as:

$$U = \sqrt{U_{T_{in}}^2 + SD_{in}^2 + U_{T_{out}}^2 + SD_{out}^2 + U_{\mathrm{Pr}_f}^2 + U_{\mathrm{Pr}_A}^2 + U_{\lambda_1} + U_\beta + U_\nu}$$
$$= \sqrt{2.5^2 + 2.36^2 + 2.5^2 + 1.51^2 + (2 \cdot 0.015)^2 + 0.27^2 + 0.34^2 + 0.6^2}$$
$$= 4.56\% \tag{6}$$

Indicated measurement uncertainty does not include uncertainty introduced while setting up the desired sample porosity value.

Results obtained through measurements of thermal conductivity of Styropor®, collected by implementing methodology described, enabled the corrected value for thermal conductivity of the baled biomass sample to be determined.

3. Analysis of experimental results

A total of nine experimental campaigns were conducted using the experimental installation and the methodology described. Experiments were performed with oilseed rape samples. Additional measurement campaign was conducted with Styropor® sample in order to validate experimental method employed i.e. to determine the absolute measurement error of the installation used.

Temperature data collected during the experiments performed, shown in Table 3, were used to determine stagnant thermal conductivity.

Results of thermal conductivity calculations, performed in accordance with methodology described, are presented in Table 4 and Fig. 4. The difference obtained when determining thermal conductivity of Styropor® sample, whose declared conductivity equals $\lambda = 0.045$ W/m K, was adopted to be the absolute measurement error of the experimental installation used. This measurement error was attributed to the effects associated with the thermal bridges and imperfections in the insulation material installed.

As shown in Fig. 4, stagnant thermal conductivity of oilseed rape residues decreases with reduced porosity. This trend continues until porosity is reduced down to 0.65. After that, with a further reduction in sample porosity, stagnant thermal conductivity begins to increase. Analysis of the most frequently used porous-bed related heat transfer models, described by Eqs. (2–4), reveals that all three functional correlations embedded in the models show that stagnant thermal conductivity increases as a result of reduced porosity. This statement is valid in cases when solid phase thermal conductivity is higher than thermal conductivity of the fluid ($\lambda_s/\lambda_f > 1$). In this case, fluid behaves as some sort of an insulator, causing heat transfer rate to be reduced as a result of increased amount of fluid i.e. increased porosity. It is assumed that pores are sufficiently small and that no fluid flow may be developed between pore walls. The case examined in the experimental investigation presented herein represents one such case, since fluid-related thermal conductivity, that is equal to thermal conductivity of air at its mean temperature of $T = 50$ °C, equals $\lambda_f = 0.026$ W/(m K). Matrix composition of the porous bed was obtained based on the arrangement of oilseed rape stems. Since stems have ligneous structure, it can be assumed that solid phase thermal conductivity is approximately equal to wood conductivity, which equals $\lambda_s = 0.1$ W/(m K)[26].

After analyzing the porous structure of the examined sample, it is concluded that the sample is constructed of open and closed pores, as defined in the introductory section of the paper. Open pores, in this case, are located between the stems of the oilseed rape, while closed pores are formed from cavities in the stems themselves. In the same time, it is obvious that open pores are considerably larger in size than closed pores. However, since the analyzed case refers to the case of stagnant thermal conductivity (with no external fluid flow), thermal conductivity is equally affected by both open and closed pores, with only difference seen in the size of the pores. Therefore, when compressing biomass sample (and reducing its porosity), the volume of open pores, located between the plant stems, starts to reduce first. Fluid inside the pores (in case that there is no external flow), can only flow inside the pores i.e. between the pore walls surrounding the fluid. In that manner, heat is transferred by natural convention from one pore wall to the other, with fluid acting as a heat transfer medium which increase total heat flow through the porous bed. Reduced porosity of oilseed rape sample causes open pores to be reduced in volume, as well as to be split into smaller fragments. As a result, fluid circulation inside the pores decreases, consequently reducing the heat transfer between the pore walls. This fact can be used to explain the results obtained in the experimental investigation conducted, leading to the conclusion that thermal conductivity reduces as a result of reduced sample porosity (until porosity reaches the value of 0.65).

As observed during the experiments performed, further reduction in sample porosity causes different changes in thermal conductivity of the sample (Fig. 4). This can be attributed to significantly reduced pore volume, causing open pores to become close in size to the closed pores. This means that the fluid flow inside the open pores is now prevented, causing the previously described positive impact on the increased heat transfer rates to cease. Additional porosity reduction occurs at the expense of reduced size of open as well as closed pores, meaning that thermal conductivity continues to increase with further reduction in porosity, as described by (3) i.e. (4). Fig. 5 provides detail presentation of the phenomena addressed (using the known λ_o models), observed as a result of reducing effective porosity below the value of 0.65.

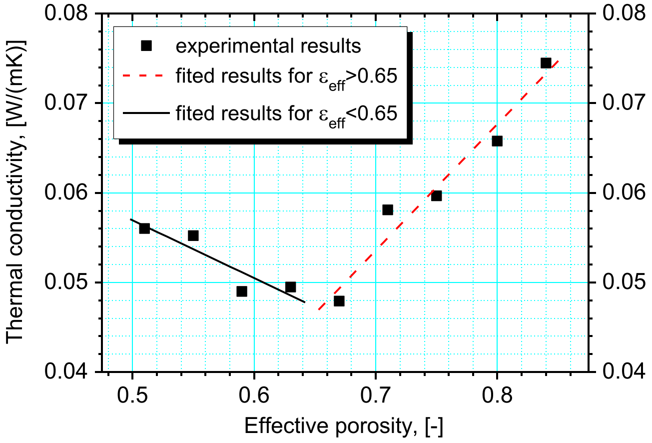

Fig. 4. Functional correlation between stagnant thermal conductivity and porosity of oilseed rape.

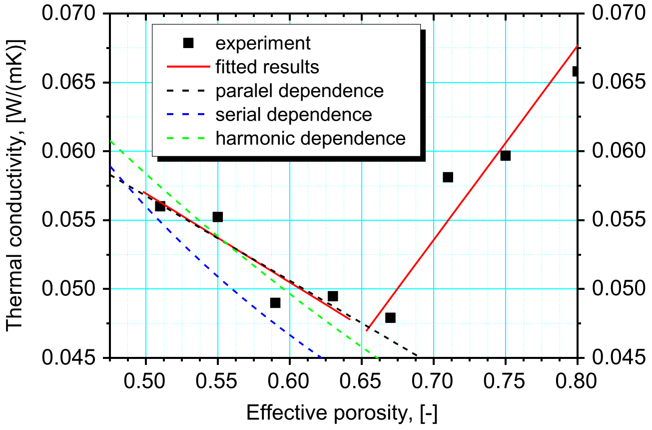

Fig. 5. Analysis of functional correlation between stagnant thermal conductivity and porosity of oilseed rape.

The dotted line seen in the graph represents a linear function obtained by least-square fitting of experimental data. Using the model based on the assumption of parallel heat transfer mode through the porous bed and applying the model to experimental data obtained, fluid-related thermal conductivity of $\lambda_f = 0.026$ W/(m K) and solid phase conductivity of $\lambda_s = 0.0875$ W/(m K) are obtained [27].

$$\lambda_{par} = 0.026\epsilon_{eff} + 0.0875(1 - \epsilon_{eff}) \tag{7}$$

Different results are obtained when harmonic heat transfer model is used, where fluid related thermal conductivity of $\lambda_f = 0.026$ W/(m K) and solid phase thermal conductivity of $\lambda_s = 0.131$ W/(m K) are obtained [27].

$$\lambda_{harm} = 0.131^{1-\epsilon_{eff}} \cdot 0.026^{\epsilon_{eff}} \tag{8}$$

Series model is practically impossible to use when analyzing the porous bed addressed in the research investigation presented herein, since it was observed that the model does not correlate well with experimental data obtained. This was the case even when fluid and solid thermal conductivity of $\lambda_f = 0.028$ W/(m K) and $\lambda_s = 100$ W/(m K) were used [27].

$$1/\epsilon_{eff} = \epsilon_{eff}/0.028 + (1 - \epsilon_{eff})/100 \tag{9}$$

However, generally speaking, neither one of the models addressed above is suitable to be used for combustion of oilseed rape bales, since the packing manner of solid and fluid phase cannot be considered to be of regular character. For the said reason, fitting of experimental data is preferred.

Based on the above, it is concluded that the reduced pore volume, associated with reduced porosity, until porosity reaches the value of 0.65, occurs at the expense of reduced size of open pores. After that i.e. when open pores become similar in size to closed pores, convective heat transfer inside the pores stops to play an important role in total heat transfer rates, with the standard models becoming the predominant heat transfer mechanisms. Based on the experimental data obtained, two stagnant thermal conductivity expressions are proposed:

$$\lambda_o = 0.08917 - 0.06447\epsilon_{eff} \ \ za \ \ \epsilon_{eff} < 0.65 \tag{10}$$

$$\lambda_o = -0.04511 + 0.14097\epsilon_{eff} \ \ za \ \ \epsilon_{eff} > 0.65 \tag{11}$$

Experimental data collected during the research investigation conducted with an aim to determine thermal conductivity of baled oilseed rape, which were summarized and presented by expressions (10) and (11), provide a solid ground for further investigations of combustion transport processes.

Character of obtained dependence of thermal conductivity on porosity can be compared to the dependence obtained by Y. Asakuma and T. Yamamoto [28] for stochastic distribution of pores in a porous medium. This comparison makes sense only for comparing the character of dependence of thermal conductivity on porosity, but not to compare the concrete values of thermal conductivity, because here are different types of porous layers involved.

Besides, the collected data may be used quite successfully for transport process modeling. The experimental procedure developed is considered suitable for creating a comprehensive database of thermal conductivity data associated with different species of biomass feedstock.

4. Conclusion

The paper presents an experimental method developed for determination of stagnant thermal conductivity of porous bed constructed of baled agricultural residues. In addition, the paper also addresses the impact of reduced porosity on thermal conductivity of the bed examined. In order to properly simulate processes occurring during combustion of baled agricultural biomass in cigar burners, sample porosity was varied over a wide range i.e. from 0.50 to 0.85. The experimental methodology and installation employed were designed in such manner to be appropriate for the range of sample porosity values that may happen during combustion conditions encountered in practice. In addition, the fact that large sample size reduces the error introduced by assumed isotropic sample structure has also been taken into account. Experimental installation was designed and constructed so as to be robust enough to enable both of the said conditions to be met, enabling sample porosity to be varied from 0.5 to 0.85 and simulating isotropic sample features. A series of experiments were performed with oilseed rape residues, with porosities varied over the indicated range. In addition, control measurement was also conducted with a material of known thermal conductivity in order to determine necessary adjustments that needed to be made to the values measured.

Experiments performed have indicated that stagnant thermal conductivity decreases with reduced porosity of the sample. This occurs until porosity is reduced from initial 0.85 down to 0.65. After this, a further reduction in porosity causes stagnant thermal conductivity to increase. Reduction in stagnant thermal conductivity recorded for sample porosity interval of 0.85–0.65 can be attributed to decreased volume of closed pores, reducing fluid circulation inside the pores and consequently reducing heat transfer between the pore walls. It is important to mention that investigation performed rested on the assumption that porous matrix of oilseed rape bale had isotropic character.

Further reduction in sample porosity i.e. below 0.65 results in increased thermal conductivity of the sample. This is attributed to the fact that heat conduction through fluid and gas phase becomes the predominant heat transfer mode. Experimentally obtained correlations between stagnant thermal conductivity of porous bed formed by baled oilseed rape and its porosity (10) and (11) were and shall be used in future furnace design. In addition, experimental data collected during the investigation performed should also be used for detailed CFD simulation of baled biomass combustion.

Own experimental installation was developed and used to obtain the data base on thermal porosity of baled biomass. Tests were conducted on a sample of sufficiently large volume so as to represent real conditions occurring in furnaces with cigar combustion of biomass.

Experimental method developed can be successfully employed for analysis of any kind of baled agricultural biomass used in combustion processes.

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