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EFFECTIVE SPECIFIC HEAT OF WOOD BRIQUETTES

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Abstract:
The effective specific heat of wood briquettes was determined by using a mathematical model developed for bulk pellets/briquettes and by measurements made in parallel and perpendicularly to the briquettes axis in the range of moisture contents below and above equilibrium moisture content. The mathematical model was based on the assumption that bulk pellets/briquettes are a porous system, consisting of solid particles and gas, with effective thermal properties. The model applied to the briquettes with the moisture content above the equilibrium moisture content is different to that applied to the briquettes with the moisture content below equilibrium moisture content, since alongside with wood fiber swelling, the magnitude and the number in the voids between chips increases. That is why, the briquettes density decreased in this moisture content range. New equations are proposed for this moisture content range considering a larger wood cell lumen that includes the chips interspaces. Experiments were performed at the temperature of briquettes ranging from 19 to 24°C and the average moisture content from 0 to 22.7%, dry basis. When increasing the moisture content above equilibrium moisture content, the briquettes expanded due to fiber swelling, but also due to the increase in the magnitude and number of chips interspaces. Both swelling and increase in briquettes voids influenced the effective specific heat.

Key words: *wood briquettes; effective specific heat; moisture content; transient line heat source method.*

INTRODUCTION

Romania is estimated to have a biomass energy potential of 7,594,000 toe/year corresponding to 19% of the total average primary consumption, which is identified in firewood and wood waste from harvesting operations (1,175,000 toe/year), sawdust and wood waste from wood processing operations (487,000 toe/year), agricultural waste (4,799,000 toe/year), biogas (588,000 toe/year) and household waste (545,000 toe/year) (Borz et al. 2013). Wood-processing residues (fine waste), such as sawdust and wood shavings, are considered to be of little economic value. They are either burned on site or transported to disposal sites. Compressing the low density biomass into a solid fuel of a convenient size and shape allows burning them in the same way like wood or charcoal. In this situation, briquettes could offer a means of waste management (Chaney 2010).

Briquettes are manufactured by compression of residues with a low moisture content (<25%, dry basis) at moderate to high pressure (>5MPa). Briquetting increases the bulk density of the biomass, increasing its energy density (the energy content per unit volume of material) (Chaney 2010).

Biomass fuel properties for the combustion analysis are grouped into physical, chemical, thermal and mineral properties. The thermal properties are specific heat, thermal conductivity and emissivity that vary with moisture content, temperature and degree of thermal degradation (Saidur et al. 2011, Ragland et al. 1991). Knowing the thermal properties of biomass briquettes and pellets is important for modeling the combustion process. Effective thermal conductivity and specific heat of bulk wood pellets are also important properties for studying self-heating during their storage (Guo et al. 2012). A packed bed of pellets is assumed by Guo et al. (2012) and Guo (2013) to be a continuous homogeneous porous system with effective thermal properties. Sjöström and Blomqvist (2014) used the transient plane source technique to measure the specific heat and thermal conductivity of bulk wood pellets within a temperature range of 22 and 120°C. They also investigated the possibility of measuring those properties on individual pellets while studying the moisture content dependence. The effect of moisture content on thermal properties of alfalfa pellets was studied by Fasina and Sokhansanj (1995) using the line heat source method for pellets moisture content ranging from 7.5 to 18%, wet basis. Specific heat and thermal conductivity of softwood, softwood bark and softwood char were comparatively measured at temperatures between 40 and 140°C by Gupta et al. (2003).

As compared to wood, which is an anisotropic and heterogeneous biological porous material, briquettes are considered to be isotropic because of the random orientation of fibers during the briquetting process. There is less information on specific heat of a single wood briquette and its dependence on moisture content and no information about its values if it is measured in parallel or perpendicularly to the briquette axis.

OBJECTIVE

The objectives of the research reported below were to investigate the specific heat of wood briquettes by measuring it using the transient line heat source method and by modeling it using the mathematical model developed for the effective specific heat of bulk pellets/briquettes. Both, measurement and modeling were carried out for moisture contents ranging from 0% to equilibrium moisture content and from equilibrium moisture content up to the maximum moisture content (24.5%, dry basis) permissible for briquettes to maintain their shape. Also, specific heat measurements were performed in parallel and perpendicularly to the briquettes axis.

MATERIAL, METHOD, EQUIPMENT

The briquettes were formed by compression of wood processing residue, i.e. softwood and hardwood chips in uncontrolled amounts, in a hydraulic briquetting press (MB4 Goldmark). Compression is a continuous extrusion process which depends on the friction forces from the side of the die acting to produce compression. The pressure used to form cylindrical briquettes with densities between 750 and 800kgm^{-3} was 150bar. The resulting dimensions of the briquettes were 40mm for the diameter and 30-75mm for the length. The maximum moisture content required by the producer of the briquetting press is 17%. No binders were used in forming the briquettes.

Twenty briquettes were selected for thermal conductivity and specific heat measurements from a lot of 200 extruded briquettes. They were stored in the Laboratory of Heat Transfer at 20$\pm$1^{o}C and 45$\pm$2 %RH. Two lengths and two diameters of each briquette were measured using a digital pocket caliper (ULTRA, 0.01 mm accuracy). A stereometric method (Rabier et al. 2006) was used to determine briquette density. This method was chosen and not a displacement method, in order to preserve the structure of the briquettes which otherwise could have alter the measurement of thermal properties. The stereometric method consisted in briquettes weighing using a mass balance (KERN-EW 3000g, 0.01g accuracy), calculating the volume of the briquettes by using their main dimensions and determining the density.

The briquettes were afterwards oven dried at 103±2^{o}C to constant mass in order to determine the moisture content (dry basis). In order to prevent loss of material during briquettes handling, drying and weighing, previously dried glass pans were used. The moisture content was calculated based on wet and dry briquette masses (SR EN 13183-1-2003/AC-2004). The briquettes dimensions were measured again after oven drying and briquettes density was recalculated.

Thermal conductivity and volumetric specific heat were measured with KD2 Pro analyzer (Decagon Devices Inc.) by using a SH-1 dual-needle sensor (30mm length, 1.30mm diameter, 2 needles, 6mm spacing), based on the transient line heat source method (Chaney 2010, Speyer 1996). This method consists in the generation of a heat pulse by one probe, the response measured by the other, and a numerical analysis of the response behavior, which allows the thermal properties (volumetric heat capacity, thermal conductivity and thermal diffusivity) to be found. In order to apply the method, two Ø=1.3mm x 30mm orifices were drilled in each briquette. From the amount of twenty briquettes, nine were drilled in parallel with the briquettes axis and the other nine perpendicularly to the briquette axis. The last two briquettes were drilled both parallel and perpendicularly to the axis. Two or three measurements of the thermal properties were performed for each briquette, at 0% moisture content (*MC*) and equilibrium moisture content (*EMC*).

Thermal properties of briquettes depend on many factors, such as the material from which they are made, the density to which they are compressed and the moisture content. In the case of biomass briquettes, due to their varied nature in terms of constituent materials, the conditions under which they are formed and their moisture content, standard literature values are not available; there are likely to be significant differences between the thermal properties, not only for briquettes of different materials, but also for briquettes of the same material formed at different densities and moisture contents (Chaney 2010).

In order to determine in the present experiment the effect of moisture content on the behavior of thermal properties of wood briquettes, they were humidified in a climatic test chamber (KPK 200/FEUTRON) at 20^{o}C and 90% RH. The moisture content of each briquette was determined according to the same method (SR EN 13183-1-2003/AC-2004), the density was obtained by using the stereometric method and the thermal conductivity and volumetric heat capacity were measured with KD2 Pro analyzer. The briquettes moisture content was increased from *EMC* up to the maximum moisture the briquettes could absorb and measurements of thermal properties could be performed.

The present paper deals only with the determination of briquettes specific heat, while the models applied to the determination of briquettes thermal conductivity were explained in detail in the paper reported by Sova et al.

According to Guo et al. (2012), a packed bed of pellets can be simplified by assuming it as continuous homogeneous porous system with effective thermal properties. Similarly, for a porous material that consists of solid particles and gas, as briquettes can be regarded, the effective volumetric heat capacity (ρc_p) is approximated by the following equation:

$$\rho c_p = (1 - P_w)\rho_w c_{pw} + P_w \rho_{air} c_{p\,air} \tag{1}$$

where: c_p is the effective specific heat of briquettes ($Jkg^{-1}K^{-1}$), c_{pw} ($Jkg^{-1}K^{-1}$) and c_{pair} ($Jkg^{-1}K^{-1}$) are specific heats of wood particles and gas (air), ρ (kgm^{-3}), ρ_w (kgm^{-3}) and ρ_{air} (kgm^{-3}) are the densities of briquettes, wood particles and air, P_w is the volume fraction of gas in the wet porous material (wet porosity).

Guo et al. (2012) also considered that the effective specific heat of bulk pellets does not differ from the specific heat of a single pellet since the density of air is much smaller than the density of solid particles.

The effective specific heat of briquettes can be therefore expressed from Eq (1) as:

$$c_p = \frac{(1 - P_w)\rho_w c_{pw} + P_w \rho_{air} c_{p\,air}}{\rho} \tag{2}$$

The wet porosity is described by Eq (3), (Hunt et al. 2008):

$$P_w = \frac{(1 - V\%_{bw})P_d}{1 - V\%_{bw} P_d} \tag{3}$$

where: $V\%_{bw}$ is the volume fraction of the bound water in the cell wall and P_d is the dry porosity.

The dry porosity is obtained from:

$$P_d = \frac{\rho_{cw_d} - \rho_d}{\rho_{cw_d} - \rho_{air}} \tag{4}$$

where: ρ_d (kgm^{-3}) is the oven dry density of briquettes, $\rho_{cw_d} = 1540\,kgm^{-3}$ is the density of the cell-wall substance (Siau 1995) and $\rho_{air} = 1.193\,kgm^{-3}$ is the density of air at 20°C (Incropera et al. 2007).

The volume fraction of the bound water, $V\%_{bw}$, is calculated as a function of the moisture content from the following equation (Hunt et al. 2008):

$$V\%_{bw} = \frac{MC\,\rho_{cw_d}}{\rho_{bw} + MC\,\rho_{cw_d}} \tag{5}$$

where: $\rho_{bw} = 1115\,kgm^{-3}$ is the density of the bound water (Hunt et al. 2008).

The density of wood particles, ρ_w, is determined using the rule of mixtures. Thus:

$$\rho_w = (1 - V\%_{bw})\rho_{cw_d} + V\%_{bw}\rho_{bw} \tag{6}$$

According to Siau (1995) the specific heat of wood increases significantly with moisture content. When the moisture content is less than 5% the specific heat of wood may be calculated from the rule of mixtures (Siau 1995) as:

$$c_{pw} = \frac{1260 + 4185\,MC}{1 + MC} \tag{7}$$

where: $MC<0.5$, $t=30^oC$, the specific heat of oven dry wood at 30°C is 1260$Jkg^{-1}K^{-1}$ (Siau 1995), the specific heat of free water at 30°C is 4185$Jkg^{-1}K^{-1}$ (Siau 1995).

Specific heat also increases with temperature and according to Siau (1995) the specific heat of the dry cell wall may be calculated as:

$$c_{pw} = 1260\left[1 + 0.004\left(t^oC - 30\right)\right] \tag{8}$$

where: t^{o}C is the temperature range from 0^{o}C to 100^{o}C.

The temperature at which specific heat of briquettes was measured was 20^{o}C. Therefore, taking into account Eq (8) and the variation of the specific heat of water with temperature, Eq. (7) becomes:

$$c_{pw} = \frac{1209.6 + 4181 MC}{1 + MC} \tag{9}$$

If the moisture content of wood increases above that mentioned in Eq (7), being in the range 5% and 24%, Siau (1995) suggests another relationship, based on a previous investigation, according to which an excess in specific heat must be taken in consideration. It corresponds to approximately $418 Jkg^{-1}K^{-1}$. Thus, Eq (7) changes into:

$$c_{pw} = \frac{1260 + 4185 MC + 1674(MC - 0.05)}{1 + MC} \tag{10}$$

After rearranging terms, Eq (10) becomes:

$$c_{pw} = \frac{1176 + 5859 MC}{1 + MC} \tag{11}$$

where: *MC* ranges from 0.05 to 0.3 and $t=30^{o}$C.

At $t=20^{o}$C, Eq (11) may be written as:

$$c_{pw} = \frac{1128 + 5808.5 MC}{1 + MC} \tag{12}$$

The aforementioned equations for the determination of the specific heat are applied to the briquettes with *MC*=0% and *MC*=*EMC*. In this moisture content range, the voids between chips remain almost unchanged. When the moisture content increases above *EMC*, alongside with wood fiber swelling the magnitude and the number of the voids between chips increase too. A considerable increase in the briquette overall dimensions is noticed and for that reason the wet porosity increases, even if the moisture content increases and thus a decrease of porosity would be expected. Accordingly, in the range of moisture contents above *EMC* the wet porosity is not anymore calculated with Eq (3). In this range of moisture contents the wood cell has a larger lumen that includes the chips interspaces. The new length of the wood cell is determined from the proportionality between cell volume and briquette volume in oven dry conditions and the current moisture content conditions. It may be calculated from the following equation (Sova et al.):

$$L' = \left(\frac{V_b}{V_{b_d}}\right)^{1/2} \tag{13}$$

where: *L'* is the overall cell dimension, V_b is the briquette volume at current *MC*, V_{bd} is the briquette volume in oven dry conditions. The new lumen length, *a'*, is calculated from the equality (Sova et al.):

$$a' - a = L' - L \tag{14}$$

where: *a* is the lumen length of the wood cell, *L* is the cell dimension at a certain *MC*. The lumen length, *a*, is determined from the dry porosity (Siau 1995):

$$a = (P_d)^{1/2} \tag{15}$$

The dimension *L* is obtained from the dry and wet porosities as follows:

$$L = \left(\frac{P_d}{P_w}\right)^{1/2} \tag{16}$$

Detailed calculation of the overall cell dimension, *L*, is shown in (Sova et al.). Accordingly, the wet porosity of the briquettes with *MC*>*EMC* is determined from Eq (17):

$$P_w' = \frac{a'^2}{L'^2} \tag{17}$$

In Eq (2), the specific heat of air at t=20°C is c_{pair} =1006.86Jkg^{-1}K^{-1} (Incropera et al. 2007).

RESULTS AND DISCUSSION

From the twenty briquettes subjected to thermal conductivity and specific heat measurements, four briquettes were removed from the range of data because they broke down during humidification. The most affected were those drilled both parallel and perpendicularly to their axis. Therefore, the measurements were further performed only on 16 briquettes.

The average moisture contents of the humidified briquettes were 5.95% (*EMC*), 12.2%, 13.1%, 16.3%, 17.6%, 21% and 22.7%, dry basis. Commercial wood pellets and briquettes have a typical *EMC* of 4-8%, wet basis (Guo 2013).

The results were divided in two groups, one group comprising the briquettes drilled in parallel with the axis and the other group comprising the briquettes drilled perpendicularly to the axis.

Fig. 1 shows the experimental and modeled effective specific heat values corresponding to the longitudinally drilled briquettes with *MC*=0% and with *MC=EMC*, as function of the briquettes density. It was decided to plot the specific heat with respect to the briquettes density rather than with respect to their moisture content. The increase in moisture content from 0% to the *EMC* resulted in the linear increase of density and specific heat, which is in agreement with the statement of Siau (1995) regarding wood, that the specific heat increases significantly with moisture content. On the same figure, the specific heat of wood, described by Eqs (9) and (12), as function of density is represented too. The effective specific heat values are almost the same with the specific heat values of wood in this range of moisture contents. The low coefficients of determination (R^2) can be explained by the low number of data in this range of moisture contents. The scatter in the experimental results indicates possible differences in the local density of briquettes.

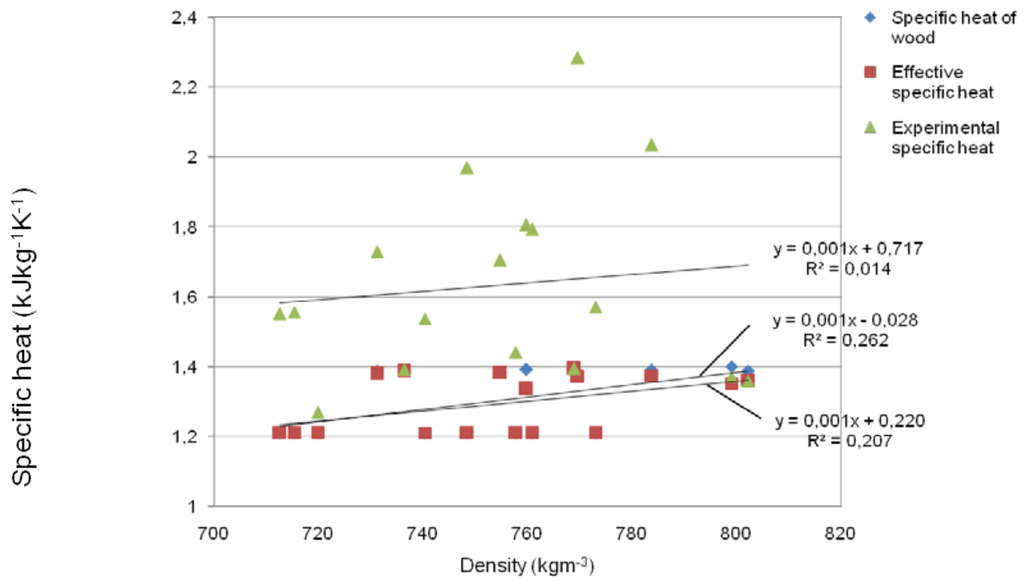

Fig. 1.
Experimental and calculated effective specific heat of longitudinally drilled briquettes as a function of density for MC≤EMC.

The experimental and modeled effective specific heat results corresponding to the radially drilled briquettes with *MC*=0% and with *MC=EMC*, as function of the briquettes density are indicated in Fig. 2. The figure also shows the results of the specific heat of wood calculated with Eqs (9) and (12). The results of the effective specific heat of briquettes and specific heat of wood are very similar to those represented in Fig. 1. They increase with density increase in a linear regression. The experimental results are again scattered and they increase very slightly with density increase.

Fig. 3 indicates the experimental and modeled effective specific heat values of the longitudinally drilled briquettes with *MC>EMC* as linear function of briquettes density. The increase in moisture content

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determined the decrease of the density because of the increase in the voids between the chips and the increase of the specific heat. The specific heat is not so much influenced by the increase in the voids as it is influenced by the increase of the moisture content. Only at moisture contents exceeding approximately 20%, the experimental results of the specific heat start to decrease because of the increase in the voids magnitude. The same ascendant trend has the specific heat of wood. Comparing the specific heat results with the thermal conductivity results, the trend is different; i.e. the briquettes thermal conductivity decreased with moisture content increase, because the density decreased and the influence of the increasing voids became predominant (Sova et al.). It also can be physically explained by the fact that the decrease in the heat transfer by conduction determines the increase in the energy stored in the briquette and less heat is required to raise the temperature by the same amount.

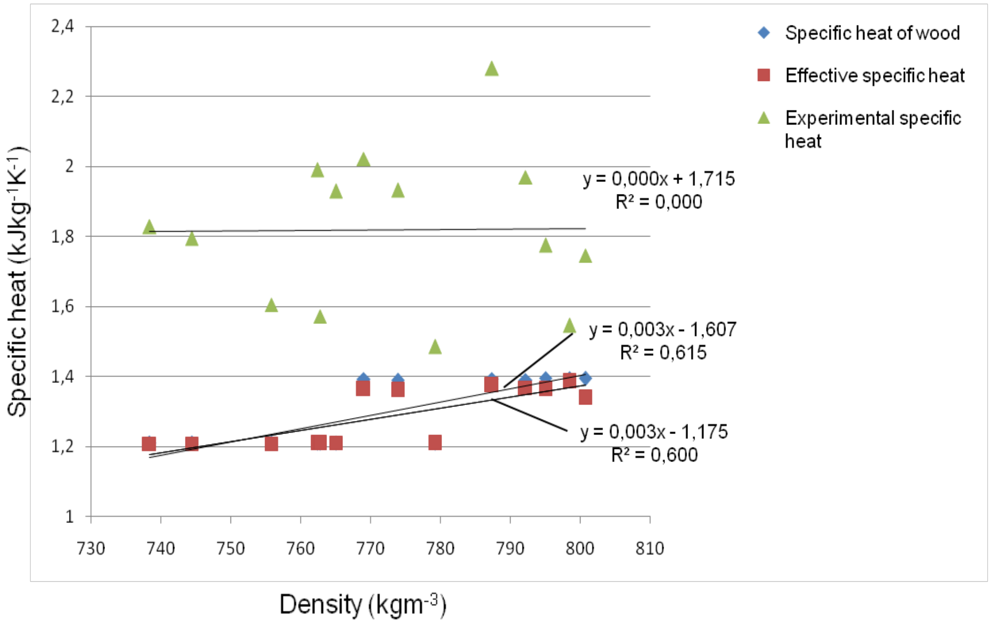

Fig. 2.
Experimental and calculated effective specific heat of radially drilled briquettes as a function of density for MC≤EMC.

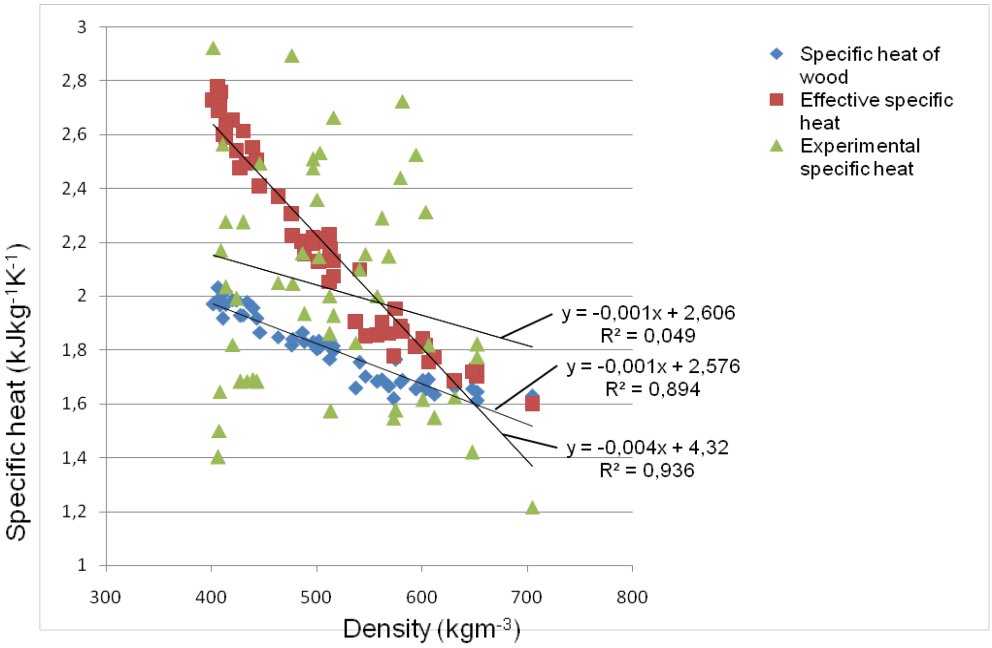

Fig. 3.
Experimental and calculated effective specific heat of longitudinally drilled briquettes as a function of density for MC>EMC.

Fig. 4 indicates the experimental and modeled effective specific heat results corresponding to the radially drilled briquettes with *MC>EMC*, as function of the briquettes density.

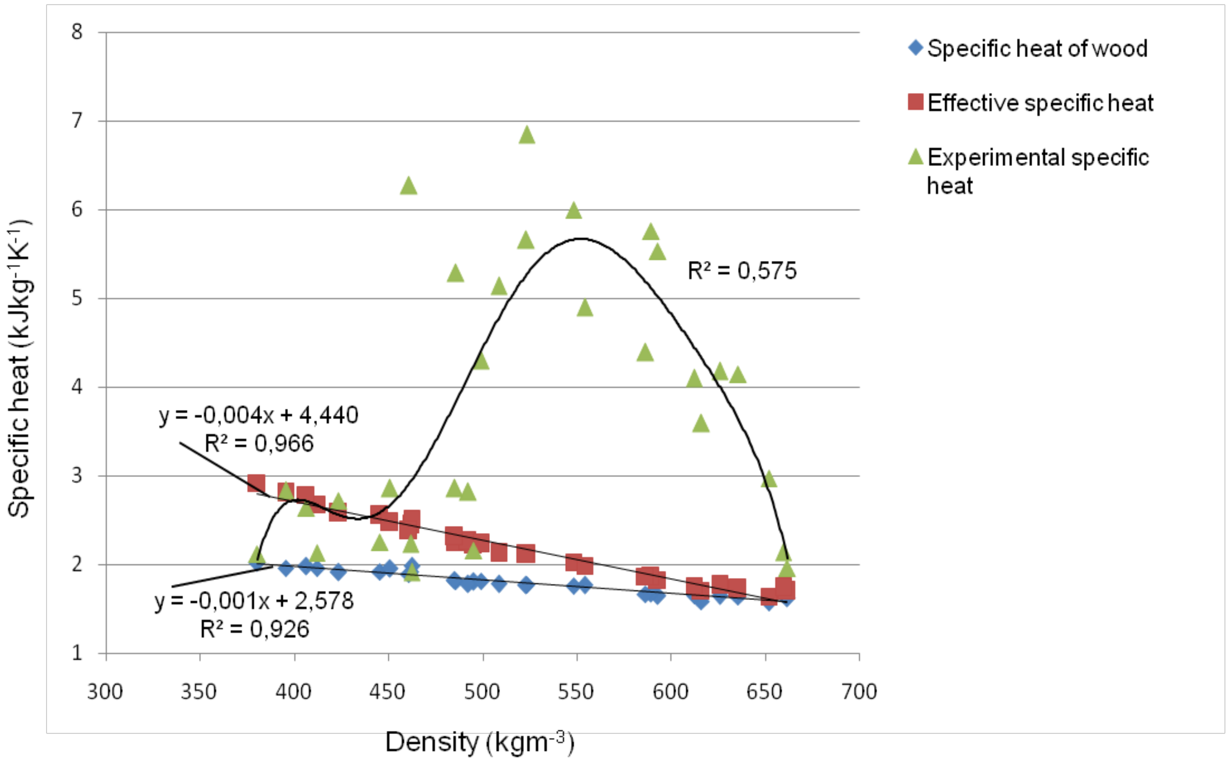

Fig. 4.
Experimental and calculated effective specific heat of radially drilled briquettes as a function of density for MC>EMC.

The increase in briquettes moisture content determined the decrease of their density and the linear increase in the effective specific heat. The specific heat of wood has the same trend and also is in linear regression with density. The experimental specific heat results increased with moisture content increase and with density decrease from 650kgm^{-3} to about 500kgm^{-3}; instead they decreased with density decrease starting with about 500kgm^{-3}. The variation of experimental specific heat with density is polynomial. Sova et al. indicated the same polynomial variation of the experimental thermal conductivity results with respect to the density of briquettes. They explained that the wood fiber swelling was more important on the briquettes length than in radial direction due to the wood swelling characteristics and that the effect of moisture content on specific heat, and thermal conductivity as well, was significant for the briquettes with the density ranging from 650kgm^{-3} to about 500kgm^{-3}. As the briquettes density decreased below 500kgm^{-3}, the influence of the voids became preponderant on both specific heat and thermal conductivity.

The experimental specific heat values are higher in case of the radially drilled briquettes than in case of the longitudinally drilled briquettes, thus depending on the measurement direction. The ratio of their average values is 1.7 (3.29kJkg^{-1}K^{-1} : 1.936kJkg^{-1}K^{-1}). On the other hand, the average values of the modeled specific heat of radially drilled briquettes and longitudinally drilled briquettes are in a ratio of 1 (1.976kJkg^{-1}K^{-1} : 1.973kJkg^{-1}K^{-1}). This shows that the modeled specific heat values are not sensitive to the measurement direction, perpendicular or parallel to the briquettes axis. It is to observe that the average experimental specific heat value of the longitudinally drilled briquettes is very close to the average modeled specific heat values. The experimental results of specific heat are therefore depending on moisture content, density and measurement direction.

The briquettes moisture content ranged from 0 to 24.5%, dry basis and the density ranged from 330kgm^{-3} (at maximum *MC*) to 802kgm^{-3} (at *EMC*). The typical range of moisture contents of wood used for fuel is from 5% to 20% (Ragland and Aerts 1991).

The specific heat of longitudinally drilled briquettes ranged from 1.217kJkg^{-1}K^{-1} to 3kJkg^{-1}K^{-1} and that of radially drilled briquettes from 1.485kJkg^{-1}K^{-1} to 6.843kJkg^{-1}K^{-1}. Guo et al. (2012) determined effective specific heat values of wood pellets with the moisture content between 1.7 and 9% that ranged from 1.074 to 1.253kJkg^{-1}K^{-1}, increasing with moisture content linearly. The bulk densities ranged from 650 to 675kgm^{-3}. The specific heat of dry wood pellets was found by the same authors to be 1.01±0.05 (kJkg^{-1}K^{-1}). In the present paper the measured specific heat of dry briquettes ranged from 1.3 to 1.99kJkg^{-1}K^{-1} (the density ranged from 720 to 763kgm^{-3}). The specific heat of dry wood at 20^{o}C, as earlier mentioned in the paper, is 1.21kJkg^{-1}K^{-1}.

Pauner and Bygbjerg (2007) assumed in their paper a specific heat of 2.2kJkg^{-1}K^{-1} for studying self-heating of biofuel pellets.

Sjöström and Blomqvist (2014) measured the thermal properties of wood pellets at elevated temperatures using the transient plane source technique. For bulk densities ranging from 502 to 693kgm^{-3} and *MC*=6.6%, dry basis, the specific heat ranged from 1.35 to 1.63kJkg^{-1}K^{-1}. They also measured the specific heat of a single pellet with the density 1290kgm^{-3} at 2.9% and 11.7% moisture content and obtained the values 1.44kJkg^{-1}K^{-1} and 1.77kJkg^{-1}K^{-1}, respectively.

Fasina and Sokhansanj (1995) reported specific heat values of alfalfa pellets ranging from 1.636 to 2.021kJkg^{-1}K^{-1} within the moisture content range of 7.5 to 18%, wet basis and at 30^{o}C temperature. They used the line heat source method to obtain bulk thermal conductivity and thermal diffusivity. The specific heat of pellets was calculated from values of thermal conductivity, thermal diffusivity and bulk density.

Chaney (2010) measured the specific heat of newspaper briquettes by using the dual probe heat-pulse method over a range of densities (175-375kgm^{-3}) and obtained the mean value of 1.612kJkg^{-1}K^{-1} in a range of values between 1.2kJkg^{-1}K^{-1} and 2.3kJkg^{-1}K^{-1}. He assumed that the specific heat of briquettes was constant across the density range tested, because the contribution of the porosity had an insignificant effect on specific heat.

The experimental results reported by the above mentioned authors are comparable to those obtained for the longitudinally drilled briquettes, as described in this paper. As regards the results of the radially drilled briquettes, they are much higher than those reported in the above mentioned papers. The literature offers no mention that any other author would have measured the thermal properties of pellets or briquettes perpendicularly to their axis. Therefore, the research must be continued with more measurements at different temperatures and moisture contents in order to completely justify the results obtained in the experiment described within this paper.

CONCLUSIONS

According to experiments and models, the effective specific heat of briquettes increased with density increase, when the moisture content increased from 0% to the equilibrium moisture content. The same conclusion can be drawn for both measurements, in parallel and perpendicularly to the briquettes axis. When the moisture content increased from the equilibrium moisture content to the maximum moisture content the density decreased and the specific heat increased. According to the experiments made in parallel with the briquettes axis, the specific heat is not so much influenced by the increase in the voids as it is influenced by the increase of the moisture content. Only at moisture contents exceeding approximately 20%, the experimental results of the specific heat start to decrease because of the increase in the voids magnitude. For the experiments made perpendicularly to the briquette axis, the results showed the polynomial increase of the specific heat with moisture content increase and with density decrease from 650kgm^{-3} to about 500kgm^{-3}. Then, the specific heat decreased in a polynomial regression with moisture content increase and with density decrease from about 500kgm^{-3}. In this case the wood fiber swelling was more important on the briquettes length than in radial direction due to the wood swelling characteristics and the effect of moisture content on specific heat was significant for the briquettes with the density ranging from 650kgm^{-3} to about 500kgm^{-3}. As the briquettes density decreased below 500kgm^{-3}, the influence of the voids became preponderant on the specific heat. The experimental specific heat values are higher in case of the radially drilled briquettes than in case of the longitudinally drilled briquettes, thus depending on the measurement direction. The ratio of their average values is 1.7. The average experimental specific heat value of the briquettes measured in parallel with the axis is very close to the average modeled specific heat value.

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