УДК 004.9

I. Malujda
Poznań University of Technology (Poland)
Chair of Machine Design Fundamentals

CONSOLIDATION PROCESS AND PLASTICIZATION BOUNDED LAYER OF MATERIAL

Описано систему, що гідравлічно приводиться в дію для безпалітурного брикетування тирси. Наведено математичну модель провідності тепла в тонкому шарі вільного матеріалу. Знання температурного розповсюдження в такому матеріалі – один з основних елементів виконання завдань тонкої вільної пластмаси матеріального шару, що застосовують під час брикетування.
Ключові слова – брикетування, температурний розподіл, моделювання процесу

This paper presents a hydraulically operated system for binderless briquetting of sawdust. In this paper the mathematical model of heat conduction in the thin layer of loose material is given. Knowledge of temperature distribution in such material is one of the basic elements of solving the problems of thin loose material layer plastic yielding in briquetting process.
Keywords – briquetting, temperature distribution, process modeling

Introduction

This paper presents a hydraulically operated system for binderless briquetting of sawdust. Besides compression, with the bulk volume reduced several times, the process involves plasticisation, necessary to obtain sufficient consolidation of the finished briquettes. Moreover, when the sawdust is being pushed through the briquetting chamber Fig.1 and then through the forming sleeve the temperature of the superficial layer rises to ca. 1300C as a result of friction [5,7]. At that temperature lignin (constituting ca. 40% of wood by weight [6]) undergoes plasticisation and in this way a cohesive and smooth bracing layer is formed on the surface when the material has cooled down to the ambient temperature [2, 5, 10]. For this process to be effective adequate parameters must be ensured during processing, including in the first place the pressing pressure and the temperature inside the forming sleeve.

In this paper the mathematical model of heat conduction in the thin layer of loose material is given. Knowledge of temperature distribution in such material is one of the basic elements of solving the problems of thin loose material layer plastic yielding in briquetting process.

System design

Mechanical briquetting machines based on piston and rod assembly are the most common type of equipment used for compression of particulate materials. High production rate which is their main advantage is obtained at the cost of service lifetime. Compaction by ramming results in relatively quick wearing of parts. In response to that a hydraulically driven bruquetting machine has been developed by the team of the Machine Engineering Unit at the Technical University of Poznań [9]. This design provides sufficient compaction pressure and eliminates the loads imposed on the pressing system by ramming, thus ensuring silent and reliable operation of the system Fig.1.

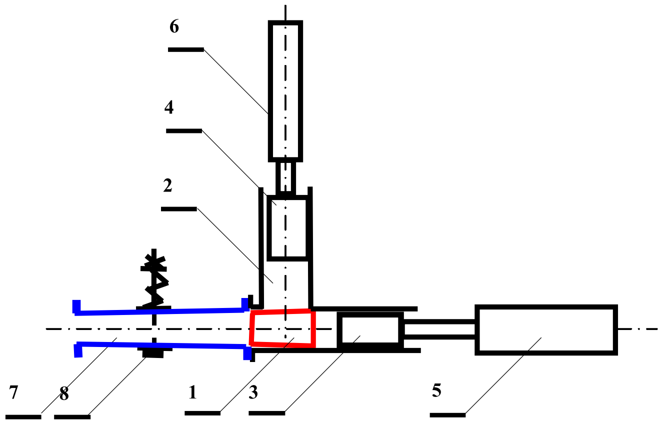

Fig.1. Kinematics diagram of the pressing unit, where: 1 – main chamber, 2 – initial densification chamber, 3 – main piston, 4 – initial pressing piston, 5 – main actuator, 6 – initial pressing unit actuator, 7 – forming sleeve, 8 - pressing resistance adjustment control

The idea underlying the design was to combine and synchronize the operation of two perpendicular mechanisms, one for pre-compression and the other for main compression stages. The pre-compression mechanism consists of the following components: pre-compression chamber 2, pre-compression piston 4 and hydraulic cylinder 6. The final compression mechanism consists of the main chamber 1, main piston 3, hydraulic cylinder 5 and forming sleeve 7 equipped with compression resistance adjustment device 8. The hydraulic cylinders 5 and 6 are connected with the hydraulic power unit by high pressure tubing. The system is controlled from control cabinet. The design of the main chamber 1 and forming sleeve 7 is critical to the effectiveness of the process. The main chamber bore has a constant converging angle in the direction of travel of briquette. The other element, the forming sleeve 7 consists of two pieces, which allows for adjusting the converging angle and in this way increasing the compression resistance. Also the length is an important factor, as it is related to the time needed to achieve the required cohesion of the finished briquette. The first model of the machine was built and then subjected to testing to optimize the process parameters, correlate the timing of pre-compression and main-compression stages (by modification of the system controlling the operation of the cylinders) and finalize the design of the mechanical parts. For continuous, unmanned and automatic feeding of waste material from the external dust collection system to the pre-compression chamber the machine may be provided with automatic feeding system. The hydraulic power and control system, although a very important part of the machine, has not described in detail in this paper.

Two design features have been claimed under patent and one, concerning the design of the hydraulic control system is subject of patent application.

Qualitative change of the briquetting pressure as a function of piston travel is presented on Fig. 2. Curve BC illustrates pushing of briquette with characteristic drop of pressure due to friction-generated temperature. The briquetting process taking place in an open chamber has been divided into the following three stages: compression - AB curve, forming (pushing through) - BC curve, expansion – CD curve.

The first stage basically takes place in the pre-compression chamber. In the final section the AB curve shows asymptotically decreasing deformation rate while the pressure in the chamber is growing rapidly. The AB curve can be described by the well-known relation expressed as exponential or power function:

$$p = a\,e^{b\rho} \quad \text{or} \quad p = a\,\rho^{b}, \tag{1}$$

where: p – briquetting pressure, a and b – empirical constants representing the properties of the raw material, ρ – density of finished briquet.

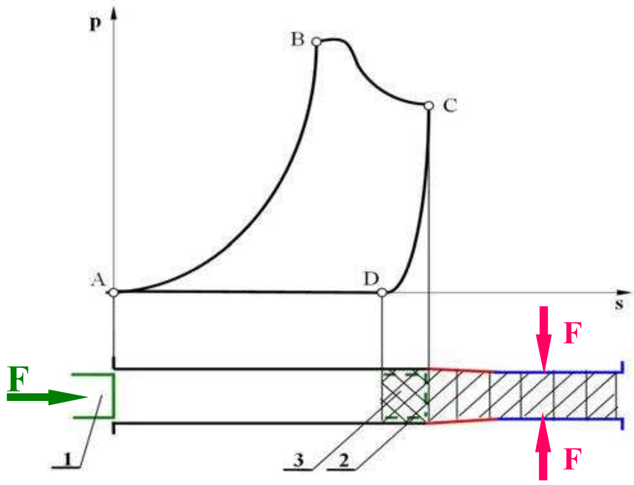

Fig.2. Change of briquetting pressure p as a function of piston travel s during uniaxial compression of briquette in an extruder barrel with adjustable taper, where: 1 – start of piston travel, 2 – end of piston travel, 3 – pressure relief phase (withdrawal of piston) resulting in unwelcome decompression of briquette

Process modeling

The upper limit of the compression force applied in an open chamber with converging bore may be established using the extreme principles of the plastic flow theory. This issue has been thoroughly covered in papers [1,8,10] and [11,12]. Therefore, for the purposes hereof it will be enough to present the conclusions resulting from them.

The problem has been solved according to the theory of plasticity and a model of ideally plastic body [3,8]. Although it is a far reaching simplification, in many cases the model provides a reasonably true representation of real life conditions. It can be used to formulate an effective plastic flow theory, which actually has been done [1].

Let us assume that the area ABCD defining the actual compression work Fig.2 may be substituted with an equivalent rectangular work area. One of the sides is determined by $\sqrt{3}$ kT, of the representative yield point of ideally plastic body, according to Huber-Mises hypothesis, and the other by the extreme strain ε_k taken from the actual material curve. The value of kT is the average stress of plastic flow, equalling the yield point of compressed material, subjected to influence of temperature.

By setting briquette compression work taken from the actual curve against the work described by the rectangle we obtain the following equation:

$$\sqrt{3} \cdot k_T \cdot \varepsilon_k = \int_0^{\varepsilon_k} \sigma \varepsilon d\varepsilon \qquad (2)$$

where: ε_k – final strain taken from the actual material curve, σ – stress during actual compression taken from the chart.

The above relation has been used to determine the average stress of plastic flow *k*, equalling the shear yield point of the compressed material. The sought-for value of compression force P will be determined from the power balance of external forces N_z used for the energy dissipation power in the plasticisation area N_d and to overcome the friction N_t.

$$N_z = P\,\nu_1 \qquad (3)$$

$$N_z = N_d + N_t \qquad (4)$$

where: ν_1 – initial speed at the entry to the axially converging main chamber Fig.3

For determining the dissipation and friction powers it is necessary to determine the distribution of displacement rate vectors at any point of the cross-section of the main chamber cone, components of the strain rate tensor and the representative strain rate.

For axially symmetrical cone-shaped chamber the plastic strain dissipation power is expressed by the following equation:

$$N_d = 3 \cdot \sqrt{3} \cdot k \cdot \pi v_1 R_1^2 \ln \frac{R_1}{R_2} \tag{5}$$

Now the equation for calculating the friction power in axially symmetrical cone-shaped chamber and forming sleeve takes the following shape:

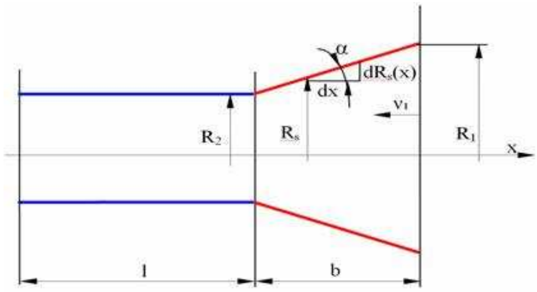

Fig.3. Compression tunnel geometry

where: R_1 – radius of the opening on the entry into the main chamber, R_2 – radius of the opening on the exit from the main chamber, R_3 – radius as a function of the main chamber's length, l – length of the forming sleeve, α – half of main chamber's taper angle, b – length of the main chamber's.

$$N_t = \mathbf{2} \cdot k \cdot \pi \cdot R_1^2 \cdot v_1 (f_1 \frac{\sqrt{\mathbf{1} + \frac{dR_s(x)}{dx}}}{\cos\alpha} \ln \frac{R_1}{R_2} + f_2 \frac{a}{R_2}) \tag{6}$$

where: f_1 and f_2 – surface roughness coefficients for the main chamber and forming sleeve respectively.

Finally, the formula for calculating the critical compression force P for conical main chamber and cylindrical forming sleeve is obtained by summing up the right sides of equations (5) and (6) and comparison against equation (4):

$$\boldsymbol{P} = 3 \cdot \pi \cdot \boldsymbol{k} \cdot \boldsymbol{R}_1^2 [\sqrt{3} \ln \frac{\boldsymbol{R}_1}{\boldsymbol{R}_2} + \frac{2}{3} (\boldsymbol{f}_1 \frac{\sqrt{1 + (\boldsymbol{tg}\alpha)^2}}{\cos\alpha} \ln \frac{\boldsymbol{R}_1}{\boldsymbol{R}_2} + \boldsymbol{f}_2 \frac{\boldsymbol{l}}{\boldsymbol{R}_2}) \tag{7}$$

Mathematical model of heat transfer

The temperature has been the key parameter in formulation of the consecutive equations describing the analysed process. There are various ways in which heat penetrates inside a body. Here, we will briefly describe two of them, which are relevant to the process under analysis due to the actual transfer of heat between the hot wall of the forming sleeve and closely abutting side of briquette. Unsteady heat conduction (which is the case here) is described by the second Fourier law [4,5]:

$$\frac{\partial T}{\partial t} = a \nabla^2 T \tag{8}$$

where: $a = \frac{\lambda}{c_p \gamma}$ – thermal diffusivity, T– temperature, t – time, γ – specific gravity, c_p – specific heat, λ – thermal conductivity.

Highly relevant to the process under analysis is to consider convective transfer of heat (Fig. 2), described by the following equation:

$$Q=\alpha\ (T_p-T_0) \qquad B_i=\frac{\alpha d}{\lambda}<1 \tag{9}$$

where: T_p – surface temperature, T_0 – temperature of the boundary layer, α – heat transfer coefficient, B_i – Biot number, d – layer thickness.

Convection is more appropriate than conduction in describing the heat transfer when the Biot number is less than one (9), and for Bi > 1 heat is transferred by conduction.

Transfer of heat by unsteady conduction is the closest approximation of the actual transfer of heat between the hot wall of forming sleeve and the briquette. The hot wall of the forming sleeve is in contact with the surface of the formed briquette, and thus we can assume that the heat transfer coefficient α tends to infinity, and consequently the Biot number (9) is greater than 1. Thus, the criterion for conductive heat transfer is met.

Therefore, the analysis of the constitutive relations describing the heat transfer between the wall of forming sleeve and the briquette will be related to conduction only.

Therefore, the role of convection and radiation has been considered insignificant and ignored in modelling the transfer of heat between the surface of hot roller and the plasticized wood surface. Conduction was assumed to be the only way in which heat was transferred in the process.

The following assumptions have between made for determination of the temperature distribution pattern:

-we deal with unsteady-state, three-dimensional conduction of heat,

-the thermal conductivity coefficient is a function of temperature,

-the effect of temperature on the value of specific heat has been taken into account,

-moisture content of oven-dried wood: 10-15%

-there is no internal heat source,

Subsequent transformations yield the following differential equation:

$$\frac{\partial \boldsymbol{T}}{\partial \boldsymbol{t}}=\boldsymbol{a}(\frac{\partial^2 \boldsymbol{T}}{\partial \boldsymbol{x}^2}+\frac{\partial^2 \boldsymbol{T}}{\partial \boldsymbol{y}^2}+\frac{\partial^2 \boldsymbol{T}}{\partial \boldsymbol{z}^2}) \tag{10}$$

The above term is known as Fourier's law describing the change of temperature in time and as a function of temperature gradient variation in 3D space. With correct boundary and initial conditions it allows for determination of time dependent temperature at any point throughout the analysed layer of material. The transformed equation (10) draws our attention to the importance of the temperature conduction coefficient a (and, specifically, to the three parameters describing it, namely: cp, γ, λ) for accuracy of the result.

For solving the problem of heat conduction in the layer of briquette the approximate solutions method was used. Following the spatial digitisation of equation (10) selection of appropriate initial and boundary conditions and approximation of the temperature field with the finite element shape function a system of simple differential equations was obtained as a function of node temperatures and their time derivatives. The system of equations may be expressed with the following differential equation:

$$[C]\frac{d}{dt}\{T\}+[K]\{T\}=\{F\} \tag{11}$$

where: [C] – heat capacity matrix, [K] – conductivity matrix, {F} – thermal force vector, {T} – nodal temperature vector.

Numerical analysis

Software program I-DEAS equipped with TMG Thermal Analysis module was used to prepare a 3-dimensional physical model of a layer of briquette on the basis of geometrical parameters (Fig.3). Spatial analysis was based on eight-nodal spatial elements of rectangular prism shape. As a result we obtain linear interpolation upon analysis of function between the nodes.

The calculations were based on the dimensions of briquettes produced by industrial machines, namely 60 mm diameter and 50 mm length. Two minute duration of briquette formation in the sleeve has been assumed to account for production capacity limitations.

Although sawdust is classified as a composite particulate material with anisotropic and non-linearly elastic behaviour for the purpose of this study the pressed material was regarded as a material continuum. This allows for determination of certain thermo-mechanical properties as the average values. Such model is fitted with equivalent coefficients, such as equivalent heat conductivity, average density. The functions characterising sawdust taken for solving the temperature distribution in a layer of briquette are given in Table 1.

Table 6

Property	Symbol	Unit	Value or function
Density in the forming chamber	ρ	kg/m^3	690
Specific heat	C_p	J/kgK	$Cp = 1350+4,46T$
Thermal conductivity	λ	W/mK	$\lambda = 0,1077T^{0,1052}$

Unsteady conduction of heat is an initial-value boundary problem for which the specific conditions must be pre-defined. In the analysed model the so-called Dirichlet's condition has been chosen from among the four basic types of boundary conditions. This condition assumes known temperature Tb(t) on the surface of briquette closely abutting the side of forming sleeve of temperature Ts. This known temperature is ca. 1300C, as this level is crucial for effectiveness of the compression process and cohesion of the produced briquette.

The initial-value conditions (a.k.a Cauchy conditions) are the values of body temperature at the initial moment t0 = 0s. Hence T(x,0) = T0(x) = 200C. Moreover, the following environmental conditions have been for calculations: temperature 200C and pressure 1,013 hPa.

The model of spatial heat conduction was solved with I-DEAS program for the above input data.

In order to increase the accuracy of temperature distribution in the thin superficial layer of briquette the density of the finite element grid Fig. 4 was increased in the contact zone between the hot forming sleeve and the surface of plasticised material. The obtained spatial distribution of temperature after 2 minutes is presented in Fig.4. Distribution of temperature on a chosen XY plane is presented in Fig. 5. As the laminar temperature distribution profile Fig. 4 does not allow for qualitative evaluation of the calculation results, they are presented as curves Fig.5 representing the increase of temperature as a function of time in the subsequent temperature layers (1,2,3,4).

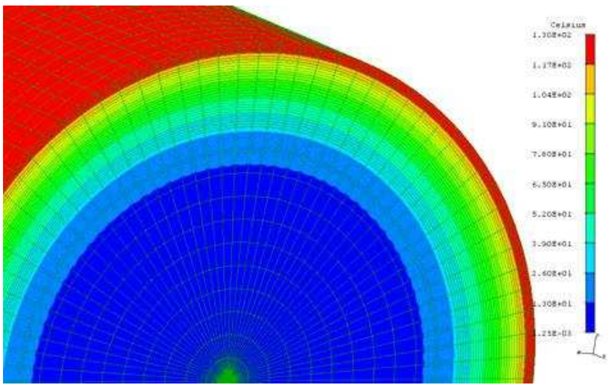

Fig.4. The spatial distribution of temperature

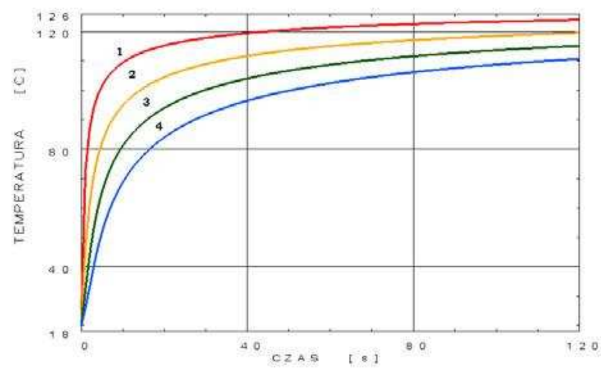

Fig. 5. Temperature as a function of time and depth inwards the briquette, where: the temperatures corresponds to the depths inwards the briquette as follows: 1 – 0.5 mm, 2 – 1 mm, 3 – 1.5 mm, 4 – 2 mm.

Final remarks

The calculated temperature distribution inside the briquette shows that for the adopted input data the temperature increases in the respective layers to ca. 1300C (0-0.5 mm depth) and ca. 110 ^{0}C (2 mm depth). We can assume that to ca. 1 mm depth the layer of sawdust becomes plasticized and at the same time overheated to the plastic flow point of lignin.

Briquetting of sawdust requires throughout densification and plasticization in the thin superficial layer under the effect of temperature. This produces a consolidated briquette with strengthened superficial layer for cohesion.

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