SIMULATION OF THE EFFECT OF MELT COMPOSITION ON MINERAL WOOL FIBRE THICKNESS

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This article presents an analysis of the influence of chemical composition of the melt on the thickness of mineral wool fibres produced industrially on a double-disc spinning machine. To calculate density, viscosity and surface tension of a multi-component silicate melt, several parameters as well as own constitutive equations were included in the model. The proposed regression model was verified and fitted by the measurement of the thickness of an industrial fibre of known chemical composition and produced under defined technological parameters, i.e. radius of spinning discs, disc rotational speed, thickness of the melt film and melt volume flow rate. Verified model brings a possibility to simulate the fibre thickness when changing both technological process parameters and chemical composition of the melt.

INTRODUCTION

Mineral wool is a general name for many inorganic insulation materials made of fibres. The material is usually divided into different subgroups depending on the raw materials they are made of, such as rock wool, glass wool and slag wool.

The most frequently used raw materials for mineral wool production are diabase, amphibolite, granite, basalt, etc., and additives such as dolomite or limestone. There are several production methods for mineralwool fibres, with a wide variation of quality and quantity of the final product [1]. The most commonly used mineral wool production process is the fiberisation of molten rock on fast rotating spinning discs [2-4]. Molten rock enters through a siphon neck into a homogenisation reservoir. Over the weir and directing channel the molten rock falls under gravity onto a rotating disc of the spinning machine. With blown-in air led coaxially over the discs, the fibres are transported away from the spinning machine and thrown into a wool chamber where they solidify into fibres of diameters about 5 µm and lengths greater than 10 mm.

The formation mechanism, as mentioned in [4], was described by Eisenklam [5]. Fibre is formed from a molten film on spinning discs. The forming and motion of the fibre depends on the inertial, viscous and surface tension forces. In addition, the solidification process is affected by the thermo-physical properties of the melt. The model describing the breaking mechanism and the formation of mineral fibres on a spinning machine is presented in [4]. The temperature, position and internal tension of each fibre are calculated during the formation phase with respect to the effects of inertial and aerodynamic forces.

The quality of the final product depends on the structure of fibres and on the proportion of solidified shots in the mineral wool. The fibre structure is characterised by its thickness (diameter), length, and the variation of both respective quantities. The material that has not transformed into fibres remains in the form of solidified shots resulting from an incomplete fiberisation process [2,3,6].

Fibres in the shape of wool can be obtained at laboratory scale. Caceres et al. [7] studied the ability of basalt melt to fiberise by means of viscosity curves. The quality of experimental fibres was enhanced through the additives $CaCO_3$ and $CaMg(CO_3)_2$. Glass fibre samples were compared with four commercial rock wool samples.

As described by Bauchage [8], and Walzel [9], density, viscosity and surface tension are very important in the liquid splitting process. The methods and instrumentation for measuring these quantities are similar for melted metals and glass melts [10].

The dependence of silicate melt density on the chemical composition and temperature is described in [11,12], where regression equations are also given for the calculation of molar volumes of multi-component silicate melts, based on the experimental data available in the literature.

The viscosity is strongly dependent on the chemical composition of the melt. Therefore, the optimal fiberisation conditions are attained for each melt at different temperatures [13]. In addition, chemical composition constrains the surface tension of the melt. Based on the results of experiments and a review of the literature, Kucuk et al. [14] set a parametric equation for estimation of surface tension of silicate melts. Goleus et al. [15] have developed similar formula for calculation of surface tension of borosilicate glasses. Multiple regression model, which enables the prediction of mineral wool fibre thickness in a real production process is presented in [16]. The model is designed on the basis of a dimensional analysis [17,18] and includes dimensionless numbers when density, viscosity and surface tension playing an important role.

With respect to the complexity of the process of developing mineral fibres, the aim of this research was to verify the multiple regression model for the prediction of fibre thickness in a real production process and to analyse the effect of chemical composition changes on the fibre thickness.

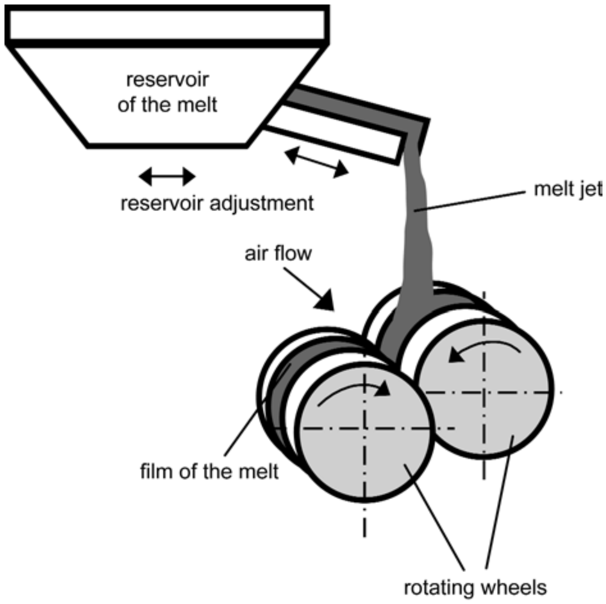

Figure 1. Schematic presentation of fiberisation process on a double-disc spinning machine.

PARAMETRIC MODEL OF MINERAL WOOL FIBRE THICKNESS MAGNITUDE

Centrifugal process of mineral wool fiberisation

The thermo-physical properties of the melt at the furnace outlet depend on the input material and on chemical reactions in various regions inside the furnace. At the furnace outlet, the melt should be homogeneous, single-phased, without any solid inclusions, and could be characterised by density, surface tension and viscosity.

Schematic presentation of the fiberisation process is given in figure 1. The molten material flows, over a system of adjustable channels, onto the first spinning disc. At the impingement point of the free jet and the first spinning machine disc, formed thin melt film is transferred via a droplet non-uniform flow onto the second disc. The melt mass rate of both discs depends on the geometric, dynamic, and thermo-physical parameters. The fiberisation process is related to the melt flow non-stability of the spinning melt film. Melt droplets - connected via surface tension and viscous forces with the melt film on the spinning disc - are drawn out of the film, and cylindrically-shaped mineral wool fibre is formed. The fibres are transferred into a coaxial airflow, which emanates through coaxial nozzles placed at the perimeter of the spinning discs. The airflow transforms the radial motion of the fibres into axial motion, and the fibres are driven into a wool chamber where the primary mineral wool layer is formed.

Dimensional analysis of fiberisation process on a double-disc spinning machine

The course of centrifugal process of mineral wool fiberisation is affected by the parameters important for rotational fluid spraying, where the fluid flow falls in a coaxial, cylindrically-shaped form onto the first disc. The key parameters and characteristic numbers of fluid flow spraying, which affected the melt spraying fiberisation process were defined by Walzel [18]:

- melt density: ρ (kg/m^3);
- dynamic viscosity: η (kg/(ms));
- surface tension: σ (kg/s^2);
- radius of the first disc: R (m);
- thickness of melt film on the disc: B (m);
- first disc rotational speed: ω (rad/s);
- melt flow rate: q_V (m^3/s).

The physical properties ρ, η, σ, are considered at melt temperature.

The basic aim of the regression model, which is presented in [16], is to determine the diameter of mineral wool fibres d_v. Based on dimensional analysis [17], three characteristic dimension N numbers can be found:

$$N_1 = \frac{\eta}{\rho R^2 \omega};\; N_2 = \frac{\sigma}{\rho R^3 \omega^2};\; N_3 = \frac{q_V}{B R^2 \omega};$$

By combining the basic dimension numbers, the following characteristic numbers can be defined:

- characteristic rotational speed number, ω^*:

$$\omega^* = \frac{1}{\sqrt{N_2}} = \omega R^{3/2} \sqrt{\frac{\rho}{\sigma}}$$

- characteristic flow rate number, q_V*:

$$q_V^* = \frac{N_3}{\sqrt{N_2}} = \frac{q_V}{B}\sqrt{\frac{\rho}{R\sigma}}$$

- characteristic viscosity number, Z:

$$Z = \frac{N_1^2}{N_2} = \frac{\eta^2}{\sigma\rho R}$$

The dimensionless numbers, ω*, q_V* and Z, characterize the process of fluid spraying on the spinning discs.

In present experiments the distance between the axes of both discs was not modified. In addition, other characteristic numbers, important for the spraying process, were taken into consideration. The important influence of temperature was considered by:

$$T^* = \frac{\Delta T}{T} = \frac{T - T_G}{T}$$

where T is the melt temperature, and T_G the air temperature.

The ratio between mass flows and dynamic viscosity of melt and gas (air) is also of significant importance [8]. This was shown by Lubanska [19], who investigated the disintegration of melts in airflow. On the basis of her empirical correlation for the determination of mean radius of droplets, (mentioned also in Bauchage [8]), a new characteristic number was defined in the present work:

$$Lu = \left(1 + \frac{q_m}{q_{mG}}\right)\frac{\nu}{\nu_G}$$

where q_m is the mass flow of melt, q_{mG} the mass flow of gas (air), ν and ν_G are the kinematic viscosity of melt and gas respectively.

In comparison with the regression model [16] we considered 6 characteristic dimension numbers, which predict the thickness of mineral wool fibres:

$$d_V = a_0 \Pi_1^{a_1}\Pi_2^{a_2}\Pi_3^{a_3}\Pi_4^{a_4}\Pi_5^{a_5}\Pi_6^{a_6} \qquad (1)$$

where a_i (i = 0, 6) are the parametric constants of the multiple regression model, and Π_i are corresponding characteristic numbers:

- Characteristic rotational speed numbers of both discs:

$$\Pi_1 = \omega_1 R^{3/2}\sqrt{\frac{\rho}{\sigma}} \text{ in } \Pi_2 = \omega_2 R^{3/2}\sqrt{\frac{\rho}{\sigma}}$$

where ω_1 and ω_2 are the respective rotational speeds of the discs.

- Characteristic number of melt flow rate: $\Pi_3 = q_v$*.

- Characteristic viscosity number: $\Pi_4 = Z$.

- Characteristic temperature number: $\Pi_5 = T$*.

- Characteristic flow ratio number:

$$\Pi_6 = Lu = \left(1 + \frac{q_V\rho}{q_{VG}\rho_G}\right)\frac{\nu}{\nu_G}$$

Temperature dependence of melt properties

The density, viscosity and surface tension of the melt plays an important role in the proposed model for calculation of mineral wool fibre thickness. Virtually all the characteristic numbers in equation (1) depend on the density, viscosity and surface tension of the melt, except the fifth characteristic number, in which temperature is dominant. Temperature dependence of density, surface tension and viscosity on the chemical composition of silicate melts must be known in order to provide an independent model for the prediction of mineral wool thickness.

Temperature dependence of density

The density of a liquid can be determined by the equation:

$$\rho_L = \frac{\sum_{i=1}^{N} x_i M_i}{V_L} \qquad (2)$$

where M_i is the molar mass of the i-th oxide in the silicate system and V_L is molar volume of the melt.

The melt density of Na_2O-K_2O-CaO-MgO-FeO-Fe_2O_3-Al_2O_3-TiO_2-SiO_2 system within a temperature range of 1573 K to 1873 K can be calculated by a regression equation [11], which takes into account that the volume of a multi-component silicate liquid is linearly dependent on the composition, with an exception of TiO_2. The molar volume V_L can be obtained from partial molar volume V_i of individual oxides presented in the melt:

$$V_L(T) = \sum_{i=1}^{N} x_i \cdot V_i(T) \qquad (3)$$

Courtial et al. [12] studied density of CaO-MgO-Al_2O_3-SiO_2 system and proposed the calculation of molar volume using the relation:

$$V_L(T) = \sum_{i=1}^{N} x_i \cdot [V_{i,1873} + (\delta V_i/\delta T)(T - 1873)] \qquad (4)$$

where the partial molar volume $V_{i,1873}$ is determined at a temperature of 1873 K.

In the present paper 67-component silicate melt was considered [11] and the molar volume $V_L(T)$ in cm^3/mol was approximated by the equation:

$$V_L(T) = \sum_{i=1}^{N} x_i \cdot V_{i,1773} + \sum_{i=1}^{N=9} \mu_i \cdot (\delta V_i/\delta T)(T - 1773)] \qquad (5)$$

Table 1 presents the values of appropriate linear regression coefficients x_i and temperature gradient coefficients μ_i.

Figure 2 shows very good agreement between the measured molar volumes of experimental melts at different temperature from 1300 K up to 1896 K and those predicted by regression analysis.

Table 1. Values of regression coefficients in equation (5) used for the calculation of silicate melt molar volume.

Oxide	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	CaO	Na_2O	K_2O
x_i	25.178	24.227	39.126	44.457	11.731	14.110	18.677	35.872	49.978
i	-0.0025	0.0027	-0.0096	-0.0229	0.0138	0.0041	0.0081	0.0158	0.0158

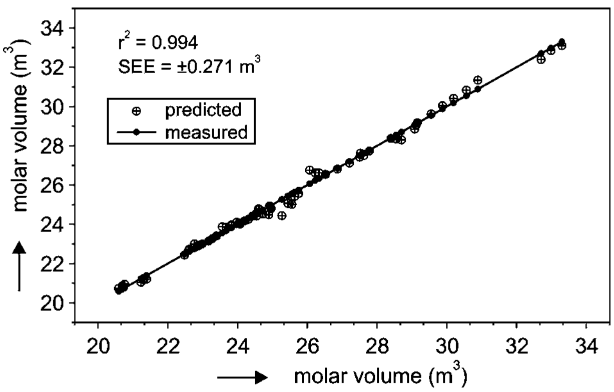

Figure 2. Comparison between measured and predicted values of the molar volume.

Temperature dependence of viscosity

Lakatos' regression model [13] was used for the calculation of temperature dependence of viscosity of the melt having known chemical composition. The model is designed for the calculation of the temperatures T(°C) when melt viscosity reaches values log η = 1.5, 2.0 and 2.5 (dPas). These temperatures can be determined with the aid of Lakatos' equation:

$$T = A\left(\frac{b_0 - SiO_2 - b_1\ Al_2O_3}{b_2 \cdot CaO + b_3 \cdot MgO + b_4 \cdot Alk + b_5 \cdot FeO + b_6 \cdot Fe_2O_3}\right) \qquad (6)$$

where b_0, b_1, b_2, b_3, b_4, b_5, in b_6 and A are Lakatos' approximation constants presented in table 2. The fractions of individual oxides are entered in weight %.

Table 2. Lakatos' approximation constants for log η = 1.5, log η = 2.0 and log η = 2.5 (dPas).

Coefficient	log η = 1.5	log η = 2.0	log η = 2.5
A	1375.76	1272.64	1192.44
b_0	122.29	117.64	112.99
b_1	1.06247	1.05336	1.03567
b_2	1.57233	1.42246	1.27336
b_3	1.61648	1.48036	1.43136
b_4	1.44738	1.51099	1.41448
b_5	1.92899	1.86207	1.65966
b_6	1.47337	1.36590	1.20929

Constants B_0, T_0 and B_1 can be calculated from Vogel-Fulcher-Tamann's equation [20]:

$$\log \eta = B_0 + \frac{B_1}{T + T_0} \qquad (7)$$

The applicability of Lakatos' model in the present article was verified for the melt having composition (wt.%): SiO_2 35-42, Al_2O_3 15-20, CaO 16-20, Fe_3O_4 2-6, MgO <12 and Na_2O <4. Figure 3 presents very good agreement between measured and calculated viscosity values with the difference up to 35 %. However, when the viscosity value at 1100°C is expelled, the relative error is only 18 %, which corresponds to the absolute error 9 dPas.

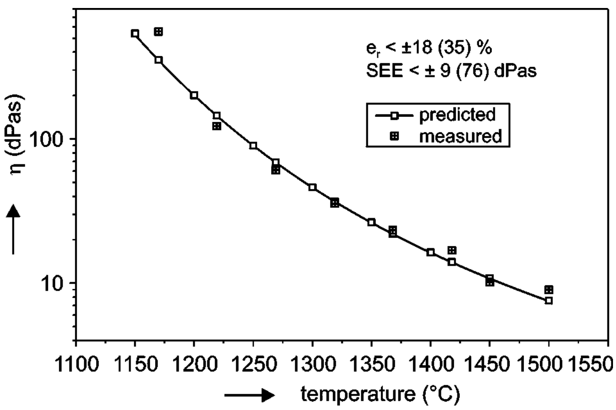

Figure 3. Comparison between the measured and calculated viscosity values of melt as a function of temperature.

Temperature dependence of surface tension

The values of surface tension σ(mN/m) at temperature 1400°C were indirectly obtained from Kucuk's equation [14]:

$$\sigma = 271.2 + 1.48v[LiO_2] - 2.22v[K_2O] - 3.43v[Rb_2O] + 1.96v[MgO] + 3.34v[CaO] + 1.28v[BaO] + 3.32v[SrO] + 2.68v[FeO] + 2.92v[MnO] - 1.38v[PbO] - 2.86v[B_2O_3] + 3.47v[Al_2O_3] - 24.5v[MoO_3] \qquad (8)$$

where v are oxide molar concentrations.

RESULTS

The experimental set-up

The experiments were performed on a double-disc spinning machine in a real production process (figure 1) at varying air mass flow q_{mG} and rotational speed of both discs, ω_1 and ω_2. The diameter and the length of both cylindrically-shaped discs were 120 mm and 385 mm, respectively. The above-mentioned quantities were independent process variables and their selection was optional. During the variation of each of the parameters, the other parameters were kept constant. The mass flow of the melt q_m, the temperature T, chemical composition and ambient parameters were measured. At each repetition, samples of melt and mineral wool were taken and the viscosity and density of melt were measured, as well as the thickness of mineral wool fibres. The rotational speed of the first disc varied in a range of 1800-5500/min, and that of the second disc in a range of 2000-5300/min. The ratio between both rotational speeds was approximately constant. The air flow rate at the spinning machine was 1.2-2.2 m/s. The melt temperature in the jet was measured by an optical pyrometer. The average temperature of the melt impinging at the disc was 1450°C.

The fibre diameters of mineral wool samples were determined by computer microscopy (figure 4). The fibre diameter varied between 4.4 and 7.5 μm, see figure 5.

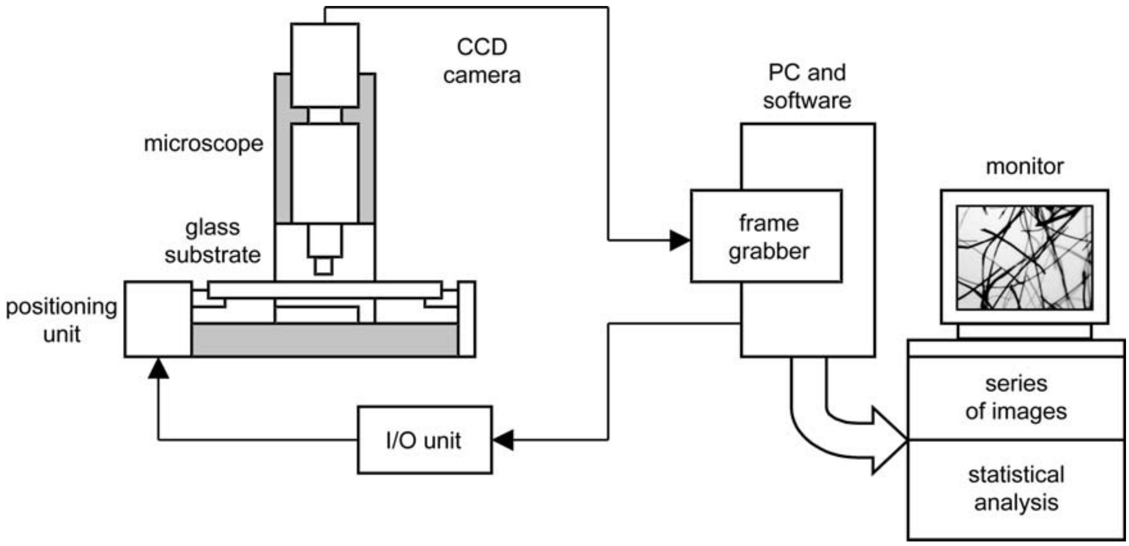

Figure 4. Computer microscopy of mineral wool fibres.

Figure 5. Micrographs of mineral wool fibres.

Statistical analysis of the results

The parameters of the regression model (equation (1)) were determined by multiple regression analysis. Table 3 presents the results of F-test [21], which was testing the hypothesis that the regression is not significant using the probability 0.0001.

Table 3. F-test results of agreement between the model and the measured values.

Source	Degree of Freedom	Sum of Squares	Mean Square	F Statistic	Prob > F
Regression	6	1206.3391	201.0565	2211.11	
Residual	30	2.7279	0.09093		
Total	35	21.8051			<0.0001

Good agreement between the model and the measured values of fibre parameters was also confirmed by the high value of multiple correlation coefficient: r^2 = = 0.88.

Table 4 presents the values of the regression model parameters a_1 - a_6, which significance was checked by a t-test.

Table 4. Regression model parameter values (equation (1)) and the results of t-test.

	a_0	a_1	a_2	a_3	a_4	a_5	a_6
Values	1	-0.358	-0.245	2.189	-0.255	-36.753	0.144
Prob > |t|		0.034	0.128	0.049	0.002	0.000	0.151

Figure 6 shows the comparison between measured fibre parameters and calculated ones. In figure 7, 95 % confidence levels for model approximation are given.

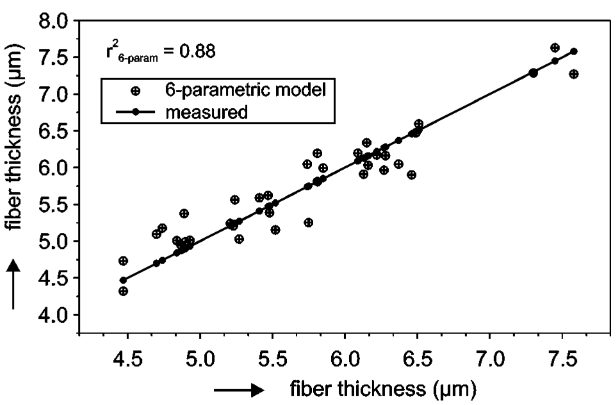

Figure 6. Comparison between experimentally measured fibre diameters and the values predicted by statistical analysis.

SIMULATION OF CHEMICAL COMPOSITION EFFECT ON FIBRE THICKNESS

The knowledge of the regression model coefficients brings a possibility to simulate the effect of the melt composition on mineral wool fibre thickness. The regression equations for calculation the temperature dependence of melt density (equations (2) and (5)), viscosity (equations (6) and (7)) and surface tension (equation (8)) were taken into account. Tables 5 and 6 present chemical compositions of the melts chosen for the simulation and corresponding melt properties at the temperature 1450°C. The composition 1, which was determined by the chemical analysis of industrial fibres, was chosen as a reference one.

Table 5. Compositions of melts (wt.%).

No.	K_2O	Na_2O	MgO	CaO	Fe_2O_3	TiO_2	MnO	Al_2O_3	SiO_2
1	0.5	2.0	11.5	23.0	3.6	1.3	0.1	19.5	38.5
2	0.5	2.0	11.5	23.0	3.6	1.3	0.1	14.5	43.5
3	0.5	2.0	11.5	23.0	3.6	1.3	0.1	24.5	33.5
4	3.0	2.0	6.5	23.0	6.1	1.3	0.1	19.5	38.5
5	0.0	0.0	11.5	23.0	6.1	1.3	0.1	19.5	38.5
6	0.5	2.0	16.5	23.0	3.6	1.3	0.1	19.5	33.5
7	0.5	2.0	16.5	18.0	0.1	1.3	0.1	19.5	38.5

Table 6. Calculated values of density, surface tension and viscosity of melts having composition presented in table 5, temperature 1450°C.

Composition	1	2	3	4	5	6	7
ρ (kg/m³)	2617	2606	2628	2592	2659	2644	2610
η (dPas)	10.94	11.41	10.53	15.34	8.57	5.20	9.03
σ (mN/m)	440	425	455	430	441	451	432

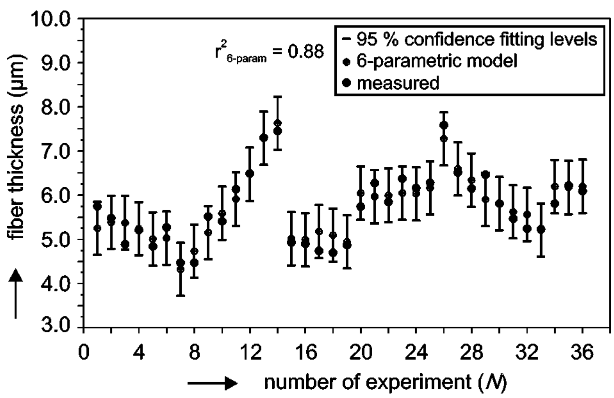

Figure 7. Comparison between experimentally measured fibre diameters and the predicted values of regression model with 95 % confidence fitting levels.

To simulate the influence of chemical composition on the fibre thickness, the constants of the regression model from table 4 were taken into account in all calculations. Other quantities (melt temperature, rotational speed, etc.) were identical with the case presented in previous chapter.

Figure 8 presents calculated results in form of the difference in fibre diameters Δd from the diameter d_{Vi} having reference chemical composition. It can be seen that the compositions 4 and 6 affect considerably the fibre thickness, whereas the effect 2, 3, 5 and 7 is lower.

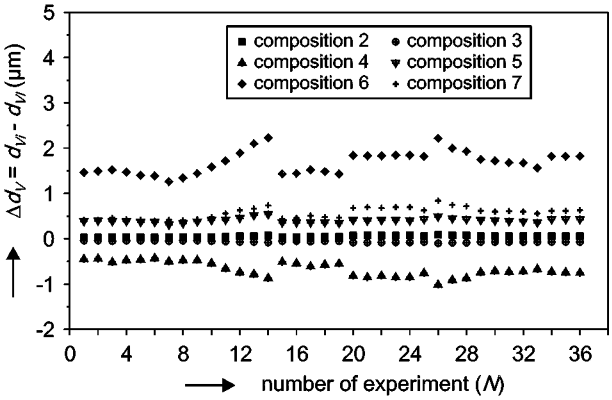

Figure 8. Influence of chemical compositions on the size of mineral wool fibres.

CONCLUSIONS

The article has verified the proposed regression model for predicting fibre thickness on an industrial double-disc spinning machine. The model brings good agreement between calculated and measured values. The knowledge of the constants of the regression model also makes possible to carry out simulations of mineral wool fibre thickness when changing the chemical composition of the melt. For this purpose, regression equations for the calculation of density, viscosity and surface tension of silicate melts were proposed and experimentally verified.

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SIMULACE VLIVU SLOŽENÍ TAVENINY NA TLOUŠŤKU VLÁKEN MINERÁLNÍ VLNY

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Článek se zabývá analýzou vlivu chemického složení taveniny na tloušťku vláken průmyslově vyráběných na dvoudiskovém zařízení. K výpočtu hustoty, viskozity a povrchového napětí vícesložkové taveniny bylo použito několik parametrů a původní konstitutivní rovnice. Navržený regresní model byl ověřen měřením tloušťky průmyslově vyráběných vláken při známém složení taveniny a definovaných provozních parametrech, tj. průměr a rychlost otáčení disků, tloušťka vrstvy a objemový průtok taveniny. Ověřený model umožňuje simulovat tloušťku vlákna při změnách technologických parametrů procesu a chemického složení taveniny.