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# Simulation of the Coating Process

**Abstract**
*Coating processes play a significant role in the area of textile production. They are used for technical textiles and special protective clothes to achieve characteristic material properties, for example water-repellency, fire resistance, high temperature protection, etc. In these processes a lot of parameters influence the coating layer's properties, which are the distance between the knife and material, the speed of the coated material going along the production line, coating paste parameters – viscosity, surface tension and density, and finally the coating material's properties – surface energy and roughness. In this paper a simulation of the knife over roll coating process is introduced and compared with experimental data taken from the measurement of coating that was applied by a laboratory coating device, Basecoater COATEMA-type, working on the basis of knife over roll technology.*

**Key words:** *coating, textile, fluid, coating machine, knife coating, blade coating, simulation of coating, viscosity, surface tension, coating thickness.*

## Introduction

Coating technology is generally a very interesting area in which many problems can be developed and solved. This paper presents a new mathematical model for the determination of the coating layer thickness after a coating process based on blade coating. So far there has been no such model described in literature which would fit the real process. Current models are not sufficient [2, 10]. The model in this study was checked experimentally by use of a laboratory semiindustrial device.

## Theoretical principles of coating

The formation of a layer on a fabric surface is typical for coating processes. The coating material parameters and substrate properties of a film are formed on the substrate surface according to the settings of the coating machine. The coating film obtained has got certain characteristics. For characterising the protective behaviour, the physical-mechanical properties of the coating film are important, and one of the most considerable physical-mechanical parameters of coating is the thickness of the coating layer [3].

The analysis and modeling of coating thickness is the main subject of this paper.

Wet coating application is a process where material in the form of a liquid is coated by moving. The total macroscopic force balance is obtained by application of the principles of elementary liquid volume movement. The force acting on the liquid volume is obtained from the change in the movement speed of the surrounding liquid.

Net forces $F_x$ acting in an x direction on the liquid element moved by the liquid speed are attained by the addition of force $F_{xB}$ (impact of volume element weight) and force $F_{xS}$ (impact of tension created in the x direction) (equation (1) [5].

$$F_x = F_{xB} + F_{xS} \qquad (1)$$

$F_x$ forces acting on the liquid element in the x direction in N
$F_{xB}$ impact of the weight of the volume element in N
$F_{xS}$ impact of tension created in the x direction in N

For an element of differential mass, $\rho dx\, dy\, dz$, equation (1) becomes

$$
\begin{aligned}
\rho dx\, dy\, dz(du_x/dt) = \\
= \rho dx\, dy\, dz\, g \cos \beta + \\
+ (\partial\tau_{xx}/\partial x + \partial\tau_{yx}/\partial y + \\
+ \partial\tau_{zx}/\partial z )dx\, dy\, dz
\end{aligned}
\qquad (2)
$$

$dx, dy, dz$ appropriate elements of distance in m
$\rho$ density of coating fluid in $kg \cdot m^{-3}$

which, on rearranging, reduces to equation (3),

$$
\rho du_x/dt = g \cos \beta + (\partial\tau_{xx}/\partial x + \\
+ \partial\tau_{yx}/\partial y + \partial\tau_{zx}/\partial z )
\qquad (3)
$$

where
$u_x$ velocity of the fluid element in the x direction in $m \cdot s^{-2}$
$\rho$ density of the fluid element in $kg \cdot m^{-3}$
$g$ acceleration due to gravity in $m \cdot s^{-2}$
$\beta$ angle the fluid element makes with the x axis
$t$ time in s
$\tau_{xx}, \tau_{yx}, \tau_{zx}$ components of stress acting in the x direction in Pa

By substituting the values of stress and rearranging the equation, we get a Navier-Stokes equation (4). This is an equation for the motion of the elemental volume in the x direction, which is used for analysis of the hydrodynamics of coating [10].

An equation describing the movement of the elementary volume in the x direction, the so-called Navier-Stockes's equation, is used for the hydrodynamic description of coatings (equation 4).

$$
u_x \frac{\partial u_x}{\partial x} + u_y \frac{\partial u_x}{\partial y} + u_z \frac{\partial u_x}{\partial z} + \frac{\partial u_x}{\partial t} =
$$
$$
= g \cos \beta - \frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{\eta}{\rho\left(\frac{\partial^2 u_x}{\partial x^2} + \frac{\partial^2 u_x}{\partial y^2} + \frac{\partial^2 u_x}{\partial z^2}\right)} +
$$
$$
+ \frac{1}{3}\frac{\eta}{\rho}\frac{\partial}{\partial x}\left(\frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} + \frac{\partial u_z}{\partial z}\right)
\qquad (4)
$$

where
$u_x, u_y, u_z$ speeds of elements of the coating material in the x, y and z directions in $m \cdot s^{-1}$
$p$ pressure due to element movement in the x direction in Pa
$\eta$ coating material viscosity in $Pa \cdot s$

In the case of blade coating processes, the coating thickness is obtained from the distance between the knife and textile material. From the point of view of easy analysis, the thickness of the coating layer is given as a function of 5 variables, which are the knife-substrate distance, substrate speed, viscosity, density and surface tension of the coating material. If the coating material is moving in the x direction, equation (4) can be reduced to a form corresponding to equation (5) [3].

$$
\frac{\partial p}{\partial x} = \frac{\eta \partial^2 u_x}{\partial y^2} + \rho g
\qquad (5)
$$

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For Newtonian liquid coating materials, the speed is obtained by equation (6), which is derived from the integration of equation (5). A schematic description of the coating application is illustrated in *Figure 1*.

$$u = \frac{u_0 y}{h} + \frac{1}{2\eta}\left(\frac{dp}{dx} - \rho g\right)\left(y^2 - hy\right) \quad (6)$$

The boundary conditions assumed are as follows: the fluid is motionless on the blade (knife), i.e. $u = 0$; the fluid velocity on the web is the same as that of the web velocity, $u = u_0$ at $y = h$. The gap between the blade and the web is $h$, which is small compared to the blade width $x$ (*Figure 1*). The coater is more like a channel, and a parallel plane flow model is used. For a Newtonian fluid, by integrating equation (5) twice and applying the above boundary conditions, the velocity is obtained as $u = u_0\,y/h + 1/2\eta\,(dp/dx − \rho g)(y_2 − hy)$

For the total amount of coating material, $Q$, going through the gap in units of length and time, equation (7) is valid [9].

$$Q = \int_0^h u\,dy = \frac{u_0 h}{2} - \left(\frac{1}{12\eta}\right)\left(\frac{dp}{dx} - \rho g\right)h^3 \quad (7)$$

$u\ (u_0)$     velocity in $g \cdot m^{-2}$
$dp/dx$     pressure gradient in $Pa \cdot s^{-1}$

The coating thickness is obtained from equation (8), created by multiplication of the coating amount $Q$ by the substrate speed $u_0$.

$$W = \frac{h}{2} - \left(\frac{1}{12\eta u_0}\right)\left(\frac{dp}{dx} - \rho g\right)h^3 \quad (8)$$

A pressure gradient is reached for the surface tension of the coating material with respect to the balance force acting along the meniscus at the top of the gap, from which we obtain equation (9).

$$\frac{dp}{dx} = -\frac{\sigma}{2h^2} \quad (9)$$

where $\sigma$ in $N \cdot m^{-1}$ is the surface tension of the fluid material.

Then coating thickness equation (10) can be formed from a combination of equations (8) and (9) [3, 9].
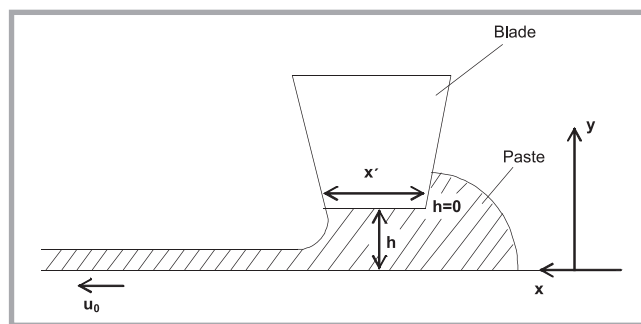
$$W = \frac{h}{2} + \frac{\left(\frac{1}{12\eta}\right)\left(\frac{\sigma}{2h^2} + \rho g\right)h^3}{u_0} \quad (10)$$

W    thickness of the fluid material after coating in m
h    gap knife/fabric in m
$\eta$    viscosity of the fluid in $Pa \cdot s$



*Figure 1. Knife coating: h - knife-substrate distance; x´ - knife width; knife: h = 0, u = 0; substrate: y = h and u = u_0 [3].*

$\sigma$    surface tension of the fluid in $N \cdot m^{-1}$
$u_0$    speed of the fabric going through the machine in $m \cdot s^{-1}$
$\rho$    density of fluid material in $kg \cdot m^{-3}$

An analysis of knife coating leads to the conclusion that the coating thickness is obtained by the addition of half the knife gap, and expressing its value depends on the surface tension of the coating material, the knife gap, coating viscosity and substrate speed.

## ■ Coating simulation

The above mentioned equation (10) gives information about the thickness of the coating material immediately after the application of wet coating. In reality, the thickness achieved after polymerisation of the coating material during the heating operation introduces a more important parameter regarding film properties.

This led to the creation of a model describing the situation after polymerisation, because by the action of heating, the thickness and mass of the coating material changes. Due to the reasons mentioned, a model for coating thickness determination was deduced. This model was formed as a result of experiments that afforded interesting results which are very different in comparison to expression (10), describing wet coating thickness.

## ■ Processing

In real industrial processes the setting of machine parameters determine basic coating properties. Another important aspect is that all coating machine variables can be changed directly in-line and become immediately operative. Therefore, in this paper two variables were selected as leading parameters and included in the modeling of the coating process: the knife-fabric gap and fabric speed. The third additional parameter used in the modeling, also important for obtaining

correct values due to the heating of the coating material, is the solid concentration in the coating material.

The modelling process was derived from the measurement of coating layer thickness carried out on one hand with different gaps between the knife and coated fabric setting and on the other with different speeds of the material guided through the coating head (placed between roller and knife).

Considering that equation (10) contains physical variables $\eta$, $\sigma$, and $\rho$, we will operate with a system where these parameters are constant and in this way resemble a real process. The stable concentration of the coating material is considered constant for the same reasons given above.

The aim of this study is to obtain a model corresponding to the facts mentioned above, with practical examples of the industrial process.

## ■ Experimental

Acrylicurethane coating paste was prepared as the coating fluid applied to fabric later on (see *Table 1*). The fabric material was cotton, a detailed description of which is listed in *Table 2*. The application of the coating material on the fabric

*Table 1. Description of fluid material used.*

| Material | Acrylicurethane |
|---|---|
| Density, $kg \cdot m^{-3}$ | 1124 |
| Viscosity, $Pa \cdot s$ | 2.47 |

*Table 2. Description of textile material used.*

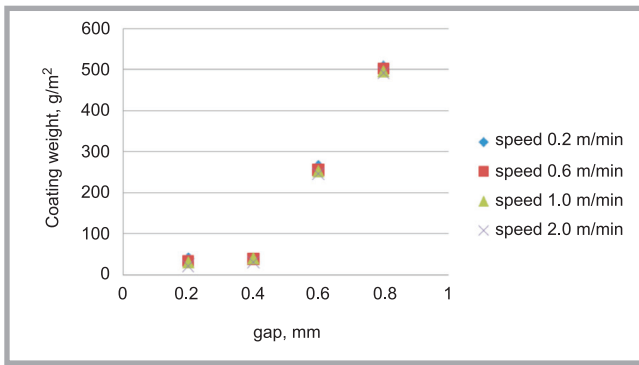| Textile type | Fabric |
|---|---|
| Material | Cotton |
| Density, $kg \cdot m^{-3}$ | 1560 |
| Surface weight, $kg \cdot m^{-2}$ | 0.225 |

**Figure 2.** *Experimental data describing the impact of the knife-fabric gap on the coating weight. 4 different velocities were used within the range of 0.2 to 2 m/min.*
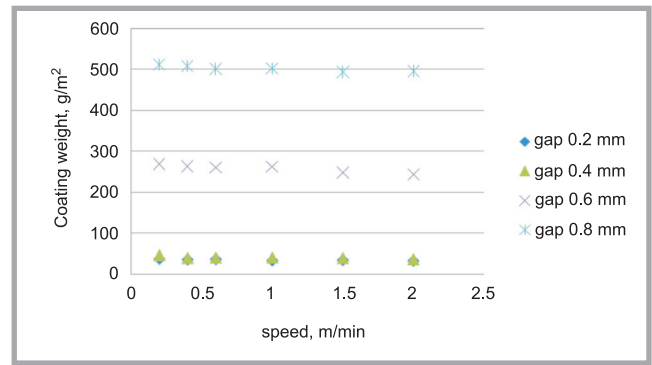
**Figure 3.** *Experimental data showing the impact of the coating machine speed on the coating weight. 4 different gaps were used within the range of 0.2 to 0.8 mm.*

was carried out by a semi industrial machine - Basecoater BC 27 Coatema.

Two sets of samples were prepared for the tests. In the first test different knife-fabric gaps were used, as mentioned in **Table 3**, at a constant fabric speed during the whole experiment, whereas in the second test samples were processed at different fabric speeds and constant knife-fabric gap (**Table 3**).

A special gauge made from metal plates of different thicknesses was used for measurement of the gap between the knife and fabric within the range of 0.01 to 2 mm. The gap was measured in the area where the fabric went in the machine, which means in the surroundings of the input roller.

The dependence of the weight of the coating layer on the knife-fabric gap is shown in **Figure 2**. A rapid tendency of an increasing coating weight is clearly visible at a gap of about 0.6 mm. Smaller gaps cause a small coating material quantity in comparison with greater gaps.

The fabrics speed, adjusted by the coating process, influences the weight of coating much less than the knife-fabric gap, of which there is a decreasing trend, which is evident from **Figure 3**, describing the dependence of the machine (fabric) speed on the coating weight.

According to the physical model (see equation (10), the coating mass before fixing in relation to the knife-fabric gap can be described by equation (11).

$$ m = \left[ \left( \frac{\rho}{2} + \frac{\sigma\rho}{24\eta u_0} \right) h + \frac{\rho^2 g}{12\eta u_0} h^3 \right] s \quad (11) $$

m  weight of fluid material after heat application in kg

s  ratio of dry mass in fluid paste used.

After the heating process the ratio of dry mass is close to 1. Although different additives are included in the fluid material,

**Table 3.** *Machine parameters adjusted during the coating process; + - fabric speed constant, o - knife-fabric gap constant.*

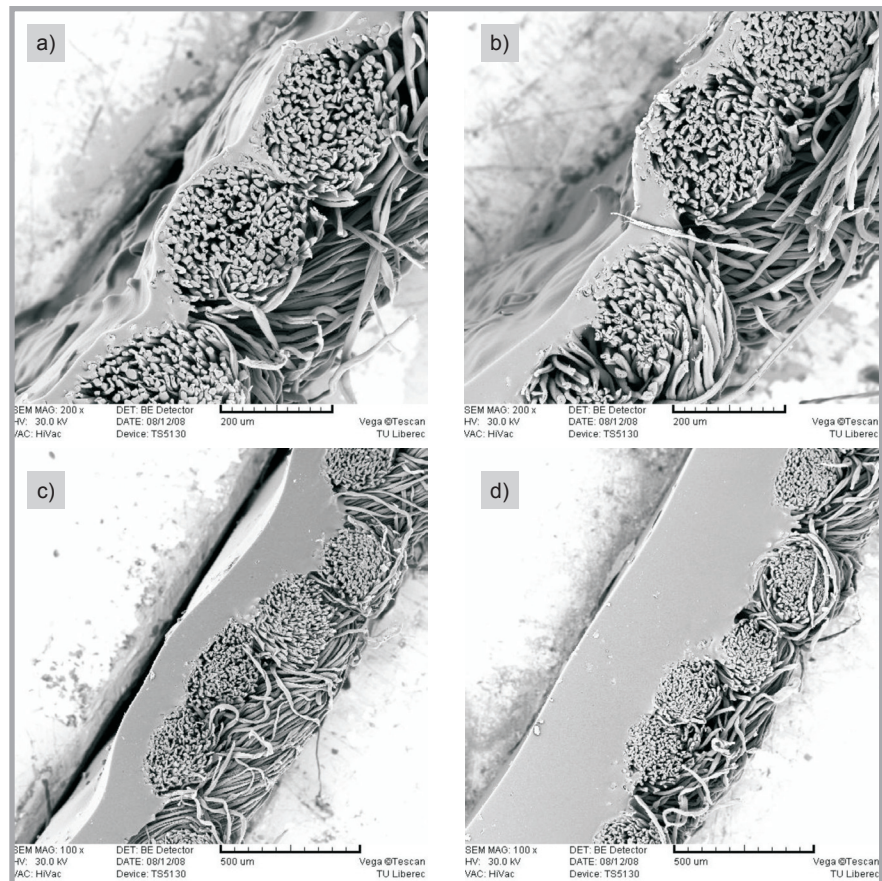| Process parameter | | fabric speed, m/min | | | | | |
|---|---|---|---|---|---|---|---|
| | | 0.2 | 0.4 | 0.6 | 1.0 | 1.5 | 2.0 |
| knife-fabric gap, mm | 0.2 | + o | o | + o | + o | o | + o |
| | 0.4 | + o | o | + o | + o | o | + o |
| | 0.6 | + o | o | + o | + o | o | + o |
| | 0.8 | + o | o | + o | + o | o | + o |



**Figure 4.** *Coating layer with gap a) 0.2 mm, b) 0.4 mm, c) 0.6 mm, d) 0.8 mm.*

they should not be calculated as they are not active components. Nevertheless, this quantity is negligible and does not need to be considered.

A model was developed of the dependence of the machine speed on the coating weight, as described by equation (12).

$$m = \left[ \frac{h\rho}{2} + \frac{\left(\frac{1}{12\eta}\right)\left(\frac{\sigma}{2h^2} + \rho g\right)\rho h^3}{u_0} \right] s \quad (12)$$

The thicknesses of particular samples were determined and acquired using scanning electro microscopy (SEM). These data were used for modeling of the coating thickness. Thickness measurements themselves were carried out by image analysis using a LUCIA G program, developed by Laboratory imaging. The change in coating layer thickness after the heating process is more complicated than the weight change described above. The experimental data were the basis for preparation of the semi-empirical model proposed.

In **Figure 4** photographs of coatings obtained from different gaps at a constant machine speed of 0.2 m/min are presented.

As the photographs show, an increase in thickness in dependence on the blade gap between the substrate and blade can be stated. A significant increase takes place at a gap of 0.6 mm, which can be compared by analysing the photographs.

Moreover, it can also be stated that a homogenous fluid covering the fabric surface is also possible, which can be clearly recognised, mostly at larger gaps (0.6 mm, 0.8 mm) at which the fluid cover the fabric surface so much, that it does not copy its shape. Faults such as surface roughness and air bubbles inside the coating layer did not appear at all.

Coatings differing according to machine speed settings are illustrated in **Figure 5**. The knife-fabric gap was constant and equal to 0.4 mm.

Experimental values of the thickness of both experimental variants – gap and speed changes are presented in **Table 4**.

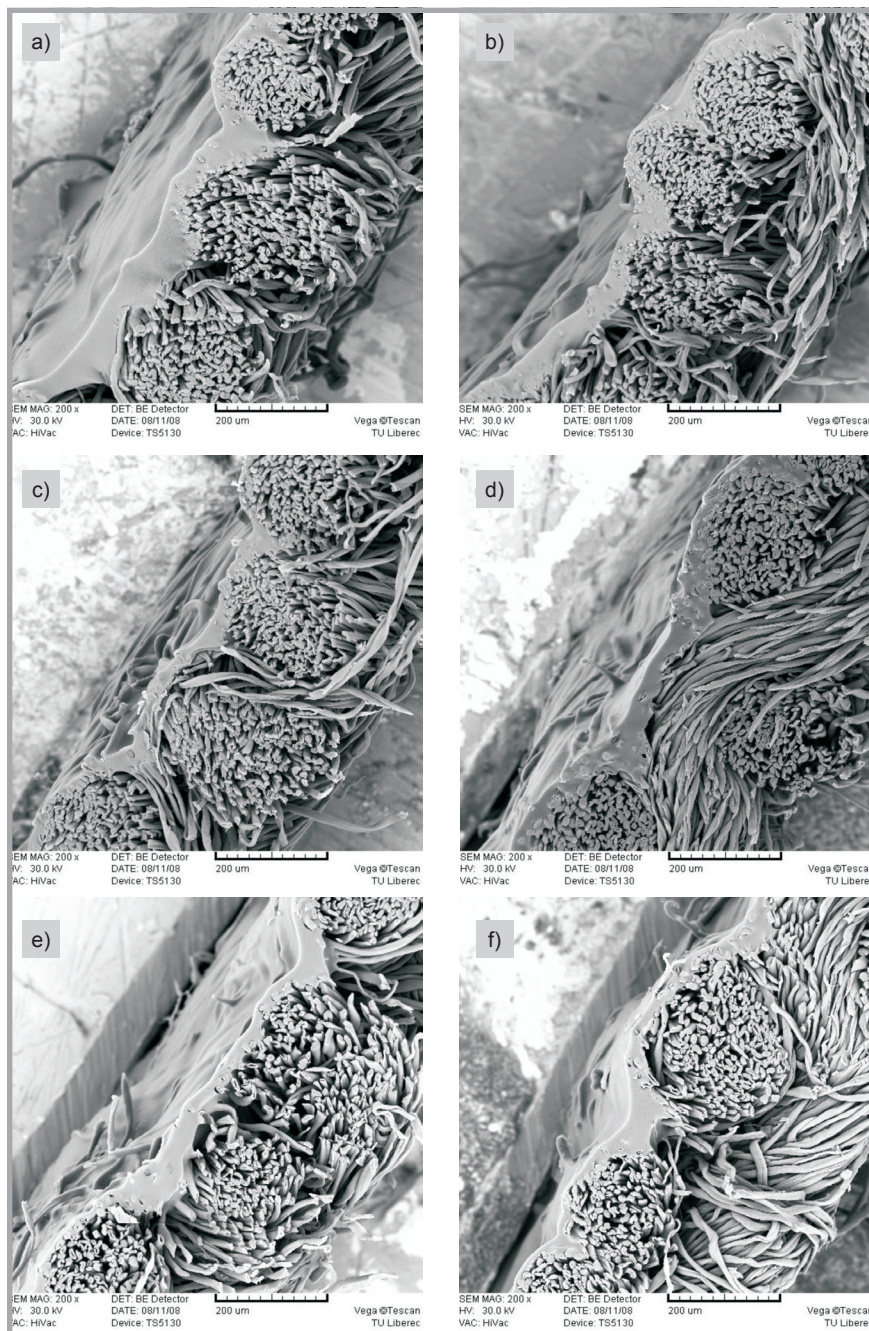The general dependence of the coating thickness is described by equation (13).



**Figure 5.** Coating layers produced by machine speed of: a) 0.2, b) 0.4, c) 0.6, d) 1.0, e) 1.5, f) 2.0 m/min; knife-fabric gap was constant and equal to 0.4 mm.

**Table 4.** Thickness data in µm in relation to the gap and speed of fabric.

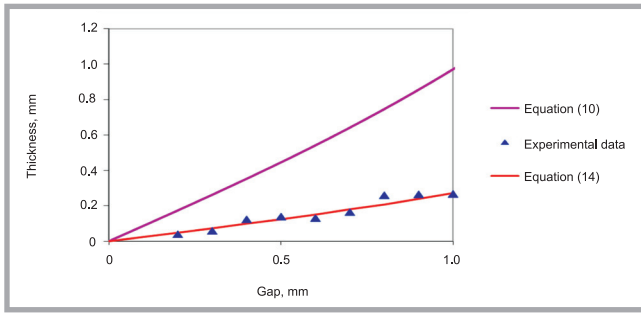| Gap, mm at fabric speed of 0.2 m/min | Thickness, µm | Speed, m.min⁻¹ at gap of 0.2 mm | Thickness, µm |
|---|---|---|---|
| 0.2 | 39.2 | 0.2 | 50.6 |
| 0.3 | 58.3 | 0.4 | 35.3 |
| 0.4 | 122.9 | 0.6 | 21.5 |
| 0.5 | 138.6 | 1.0 | 19.1 |
| 0.6 | 130.3 | 1.5 | 16.0 |
| 0.7 | 164.7 | 2.0 | 12.7 |
| 0.8 | 259.1 | | |
| 0.9 | 264.3 | | |
| 1.0 | 266.9 | | |

**Figure 6.** *Comparison of experimental data of the thickness obtained and. results from the physical model according to equation (10) and empirical model according to equation (14).*
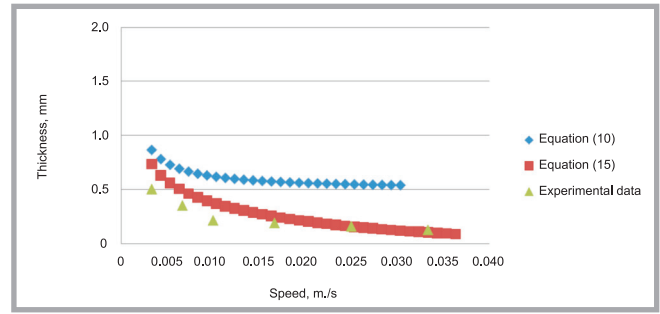


**Figure 7.** *Comparison of experimental data of thickness obtained with different machine speed values using a semi-empirical model according to equation (15) and physical model according to equation (10).*

$$W = \left[ \frac{h}{2} + \frac{\left(\dfrac{1}{12\eta}\right)\left(\dfrac{\sigma}{2h^2} + \rho g\right)h^3}{u_0} \right] - \frac{\partial W}{\partial t \partial T} \tag{13}$$

The term $\dfrac{\partial W}{\partial t \partial T}$ describes the change in thickness of the wet coating before heating, which is dependent on time and temperature.

This change depends mostly on the coating material composition and its properties. During the heating operation, the volume of the coating material decreases even if all the solvent is taken away. This volume decrease is accompanied by a thickness change. According to the experimental values obtained, an empirical approach was derived and is presented in equation (14).

$$W_M = \left[ \frac{h}{2} + \frac{\left(\dfrac{1}{12\eta}\right)\left(\dfrac{\sigma}{2h^2} + \rho g\right)h^3}{u_0} \right] \cdot s \cdot e^{-h} \tag{14}$$

**$W_M$** is a model value of the thickness established after the heating process; **s** is the percentage of the dry mass of the coating material, and term **e^-h** is an exponencial function of the knife-fabric gap.

In **Figure 6** experimental data are compared with the model function from equation (14) and the model from equation (10). A constant speed of 0.2 m/min was applied during gap measurement.

In the case of the dependence of the coating thickness on the machine speed, a model was developed and is presented as equation (15). Comparisons of the experimental data with models (15) and (10) are illustrated in **Figure 7**.

$$W_M = \left[ \frac{h}{2} + \frac{\left(\dfrac{1}{12\eta}\right)\left(\dfrac{\sigma}{2h^2} + \rho g\right)h^3}{u_0} \right] \cdot s \cdot e^{-\frac{u_0}{s}} \tag{15}$$

## ◼ Conclusion

◼ The aim of this paper was to develop semi-empirical models for prediction of thickness and mass coating. Both models result from a physical model for coating thickness determination that is only valid after coating application before heating. The new models submitted solve the problem after heat processing.

◼ The first model characterises the dependence of the coating thickness on the knife-fabric distance (gap), which is described by equation (14). A comparison of this model with experimental data obtained corresponds very well, as can be seen in **Figure 6**.

◼ The second model which characterises the dependence of the coating weight on the machine speed is described by equation (15). A comparison of experimental data obtained with the model curve is presented in **Figure 7**.

◼ Both models are suitable for use in knife coating processes and can help obtain necessary changes in coating thickness or weight during application. Although experimental checking was carried out with the use of semi-industrial equipment, Basecoater COATEMA, we can assume that the models will be valid for other machines based on the same technology. However, it should be taken into account that the models developed are valid only for the boundary conditions accepted.

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