Analytical model of foil consumption for cylindrical bale wrapping

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Abstract. The work presents an algorithm for the calculation of the consumption of stretch foil used to wrap cylindrical bales of fodder in order to isolate the fodder from the air and other external factors. Mechanical properties of the foil, its arbitrary dimensions and any overlapping width of subsequent wrapped foil layers ware taken into account. A simulation program was written that allows to compute the number of foil layers in the bale lateral surface as a function of the width of the foil, the angle of the bale's rotation around its axis and the number of wrappings. The computer program contains graphical module which allows visualization of geometry of the distribution of subsequent foil strips and the arrangement of foil layer in a bale cross-section. The length and surface area of the foil taken from the roll are computed for different variants of the wrapping process. The computational example is presented for two geometrically different ways of wrapping and different initial widths of the foil. Conclusions and suggestions were formulated as a result of the simulation.

Key words: baled silage; stretch foil consumption; simulation model

INTRODUCTION

The quality of silage in the form of cylindrical and prismatic bales depends on the efficiency of its protection against the penetration of air and impact of other external factors. Anaerobic conditions facilitate the development of desired microbes that provide for the quality of the final product [5, 6, 17]. The conventional method of producing silage consisted in placing material in a specially prepared storage sites. The currently applied method of protecting silage involves mechanical wrapping of individual bales with a 25 µm thick tear-proof stretch foil. A comparative review of chemical, physical and biological processes occurring in the silage produced in storage sites and foil bales revealed that the conventional method was characterised by much lower losses and provided the silage of better quality [1].

The main reason behind the losses of silage when wrapped with foil is the lack of required leakproofness, which leads to fermentation, decay and development of fungi in the secured material [9, 18, 19]. Four layers of foil are usually sufficient to achieve oxygen-free conditions, but using 6 layers prevents the development of mould and reduces wilting to a higher extent, whilst the density of bales is of little significance [11, 14, 15]. Stretching the foil in 50% to 70% increases its adherence to the material being wrapped and to the previously applied layers. The degree of foil extension depends on the structure of the feeding unit, roller material, foil type and thickness as well as the temperature of air [12, 13] and has a significant influence on its consumption and leakproofness [9]. Excessive stretching of the foil might be the cause of micro-cracks or its visible damaging.

Financial expenditures on the purchase of stretch foil manufactured in the form of foil sleeves and tapes on rollers constitute a high percentage in the total costs of this technology of silage production [2, 16]. Foil consumption per unit of secured volume increases along with reducing the volume of the bale. More foil is consumed for wrapping single bales than in the case of collective wrapping of several bales [13]. Furthermore, the consumption is also determined by the method of applying the foil and its uniform distribution [6, 7].

In order to define the methods of reducing foil consumption while providing the required leakproofness, different authors analyse foil consumption by applying experimental methods for different extension degrees e.g. [4, 7, 8, 17] and various width of the mutual overlapping of adjacent strips [3, 6].

To conclude, the majority of studies on the subject focuses around experimental research following two separate directions – the study of the quality of secured silage in dependence on the physicochemical processes occurring in it, and the research of the dependence of the consumption of foil from the point of view of applied wrapping methods. However, there are almost no theoretical studies concerning the economical aspect aimed at reducing the costs of the applied technology. Only a few works provide mathematical expressions for the computation of foil consumption for wrapping individual bales e.g. [7, 10]. Different parameters describing the process are taken into account in these mathematical descriptions, and estimations performed with their use are, as authors claim, close to experimental results. In order to develop a mathematical description that improves the accurateness of the estimation of the measurement results, the mechanical properties of the foil and the geometry of the overlapping of subsequent layers must be taken into account.

The aim of this study consists in the development of mathematical model and writing computer software that allows to compute the consumption of foil for wrapping separate cylindrical bales using the classic method illustrated in Fig. 1. The computations take into account the mechanical properties of the foil, which influence changes in its length and width after stretching and the width of the contact between adjacent foil strips, hereinafter referred to as overlap. The influence of the inclination angle of the foil strips relative to the cylinder height as well as the effect of the bale volume change and its deformations caused by the pressure of the foil were omitted in the study. Also, the geometry of the distribution of foil strips on the bales' top and bottom was not taken into account in the analysis.

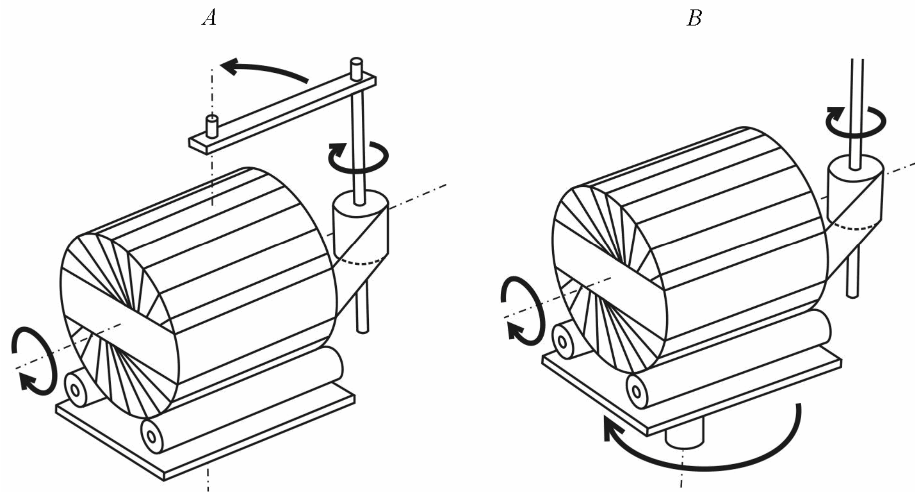

Fig. 1. Methods of individual round bales wrapping with the stretch film [2]: A – on the wrapper with a non-rotating table, B – on the wrapper with a rotating table

MATERIALS AND METHODS

Depending on the initial width of foil, its Poisson's ratio and unit deformation of the foil, the width of the foil after stretching was determined, and next the required number of wrappings was found. The distance between the edge, from which the wrapping begins, and the opposite edge of the final (applied for the final wrapping) foil strip was also determined. Then, the surface area of foil taken from the roll, used for wrapping the bale, was determined. A computing and graphic program was written to implement the derived mathematical expressions and facilitate the visualisation of the wrapping process. Exemplary computations were performed, in which foil consumption depending on its width and overlap was determined for two different values of overlap, which determine the different wrapping conditions.

FOIL CONSUMPTION

The following physical values were taken as input data for computations: D_b – bale diameter, H_b – bale height, b_f – width of unstretched foil, k_f – dimensionless relative ratio determining the width of the contact between adjacent foil strips, $0 < k_f < 1$, ν_f – Poisson's ratio of the foil, ε_{lf} – unit deformation of foil, n_b – assumed number of bale rotations around its axis.

Based on the definition of Poisson's ratio we obtain a formula, which allows to compute, for a given unit deformation ε_{lf}, its width after stretching b_{fr}:

$$b_{fr} = b_f\left(1 - \nu_f \varepsilon_{lf}\right). \tag{1}$$

We assume that the geometry of movements determining the size of overlap are applied so that the subsequent strips of foil overlap one another creating the overlap $k_f b_{fr}$. We assume that the bale is wrapped correctly, when the last applied strip of foil overlaps the adjacent strips correctly, thus creating overlap $k_f b_{fr}$ on a preceding strip and overlap not smaller than $k_f b_{fr}$ on a foil strip applied in the previous layer. This means that the number of wrappings i_o for n_b rotations of the bale:

$$i_o = \frac{\pi D_b n_b}{b_{fr}\left(1 - k_f\right)}. \tag{2}$$

Thus defined ratio i_o does not have to be (and usually is not) an integer. It provides the lower estimate of the total number of wrappings i_{oc}, hence, the number of wrappings i_{oc}:

$$i_{oc} = \lceil i_o \rceil \tag{3}$$

where $\lceil i_o \rceil$ is the smallest integer not lower than i_o (ceiling).

The ratio i_{oc} (3) not only makes it possible to determine the total number of wrappings that satisfy the assumed standard of bale wrapping, as characterised below, but is also significant for the design of algorithm for bale wrapping computations, as it allows to easily determine the "distance" z_o between the edge determining the beginning of wrapping and the opposite edge of the foil strip applied during the last wrapping. This "distance" for i_{oc} wrappings is equal to:

$$z_o = b_{fr}\left[1 + \left(i_{oc} - 1\right)\left(1 - k_f\right)\right] - \pi D_b n_b. \tag{4}$$

The above expression, including the Eq. (2) can be rewritten in an equivalent form as:

$$z_o = b_{fr}\left[(i_{oc} - i_o - 1)(1 - k_f) + 1\right] . \tag{5}$$

On the basis z_o you can calculate the required angle of rotation of the beam α_b about the axis thereof:

$$\alpha_b = 2\left(\pi n_b + \frac{z_o - b_{fr}}{D_b}\right). \tag{6}$$

The length of stretched foil L_{fr} wrapped over the bale is given by the formula:

$$L_{fr} = 2i_{oc}(D_b + H_b). \tag{7}$$

The respective surface area of foil S_{fr} is equal to:

$$S_{fr} = L_{fr} b_{fr} , \tag{8}$$

whereas the length of wrapped foil L_f taken from the roll is equal to:

$$L_f = \frac{L_{fr}}{\varepsilon_{lf} + 1} . \tag{9}$$

The respective surface area of foil S_f is equal to:

$$S_f = L_f b_f . \tag{10}$$

GRAPHIC PROGRAM

The graphic program enables visualisation of the consecutive foil layers imposition in a bale's cross-section – see Fig. 2.

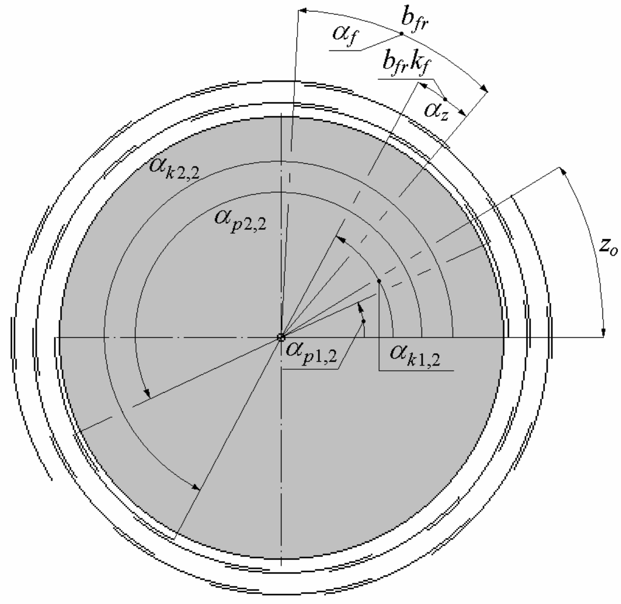

Fig. 2. The geometry of the foil layers distribution

For this purpose, the following values are computed:

- the radian measure of the central angle which subtends the arc of length equal to the width of stretched foil defined as the ratio of the length of the arc divided by the bale's radius:

$$\alpha_f = \frac{2b_{fr}}{D_b} , \tag{11}$$

- the radian measure of the central angle which subtends the arc of length equal to the width of overlap:

$$\alpha_z = \frac{2k_f b_{fr}}{D_b} , \tag{12}$$

- the radian measure of the angles of start and end of the i arc of length equal to the width of stretched foil:

$$\alpha_{p1,i} = (i - 1)(\alpha_f - \alpha_z) , \tag{13}$$

$$\alpha_{k1,i} = i(\alpha_f - \alpha_z) + \alpha_z , \tag{14}$$

- the respective radian measure of the angles of start and end of the arc of length equal to the width of stretched foil on the opposite (relative to the bale's axis) lateral surface:

$$\alpha_{p2,i} = (i - 1)(\alpha_f - \alpha_z) + \pi , \tag{15}$$

$$\alpha_{k2,i} = i(\alpha_f - \alpha_z) + \alpha_z + \pi , \tag{16}$$

- radius of the arc:

$$R_f = (D_b + g_r i)p , \tag{17}$$

where: i is the number of the subsequent foil strip (subsequent wrapping) that changes from the value of 1 to the value of i_{oc}, p is the drawing scale, and g_r is the value by which the radius of the subsequent arc is increased in the graphic program. In Fig. 2 the starts and ends of arcs for the second wrapping are dimensioned.

Based on the computed values, the cross-section of the bale, with wrapped foil strips visualised as arcs, is drawn on the monitor screen. In order to make the drawing more legible, the next arc has bigger radius compared to the previous one, whilst retaining the same arc measure.

RESULTS

NUMERICAL EXAMPLE

The following fixed bale dimensions were adopted: diameter D_b = 1.2 m, height H_b = 1.2 m, and it was assumed that the bale is to be protected by at least four layers of foil. Computations were performed for two variants of wrapping, marked with letters *A* and *B*, in which the values of the ratio determining the width of the contact of adjacent foil strips and the assumed number of bale rotations around the bale's axis for successive variants were adopted as follows: *A*: k_f = 0.50, n_b = 1 rotation; *B*: k_f = 0.75, n_b = 0.5 rotation. The remaining numerical data used in the simulation were as follows: Poisson's ratio of foil ν_f = 0.34 and unit deformation of foil ε_{lf}= 0.7.

In order to study the influence of foil width on its consumption and wrapping geometry, the length and surface area of the consumed foil as the function of foil width were changed every 0.001 m within the range b_f = 0.25-0.75 m and presented in Fig. 3. The computations were performed for two examined variants.

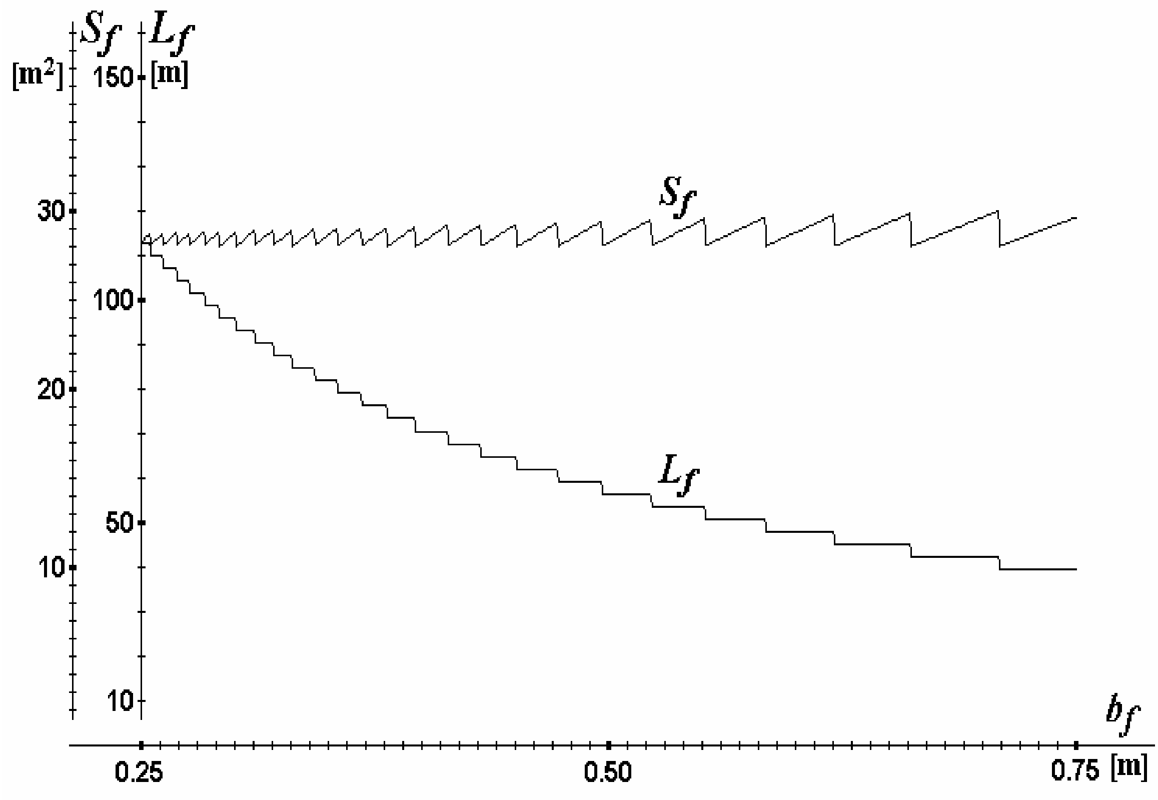

Fig. 3. The length and surface area of foil taken from the roll as the function of the foil width for variants *A* and *B*

The numerical values of computed factors and indices for three typical foil widths are presented in Table 1, whereas the cross-sections of the bales with indicated geometry of the distribution of foil strips are presented in Fig. 4.

Table 1. Numerical values of the computed factors and indices for three typical foil widths and two selected wrapping variants

Factor	Unit	Numerical value					
b_f/b_{fr}	m	0.25/0.19		0.50/0.38		0.75/0.57	
		A	*B*	*A*	*B*	*A*	*B*
$k_f b_{fr}$	m	9.50	14.25	19.00	28.50	28.50	42.75
i_o	-	39.68	39.68	19.84	19.84	13.23	13.23
i_{oc}	-	40	40	20	20	14	14
z_o	$\times 10^{-2}$m	12.53	15.77	22.03	30.02	50.53	53.77
L_f	m	112.94	112.94	56.47	56.47	39.53	39.53
L_{fr}	m	192.00	192.00	96.00	96.00	67.20	67.20
S_f	m^2	28.24	28.24	28.24	28.24	29.65	29.65
S_{fr}	m^2	36.48	36.48	36.48	36.48	38.31	38.31
α_b	rad	6.18	3.09	6.02	3.01	6.18	3.09

A: $k_f = 0.50$, $n_b = 1$ rotation; *B*: $k_f = 0.75$, $n_b = 0.5$ rotation

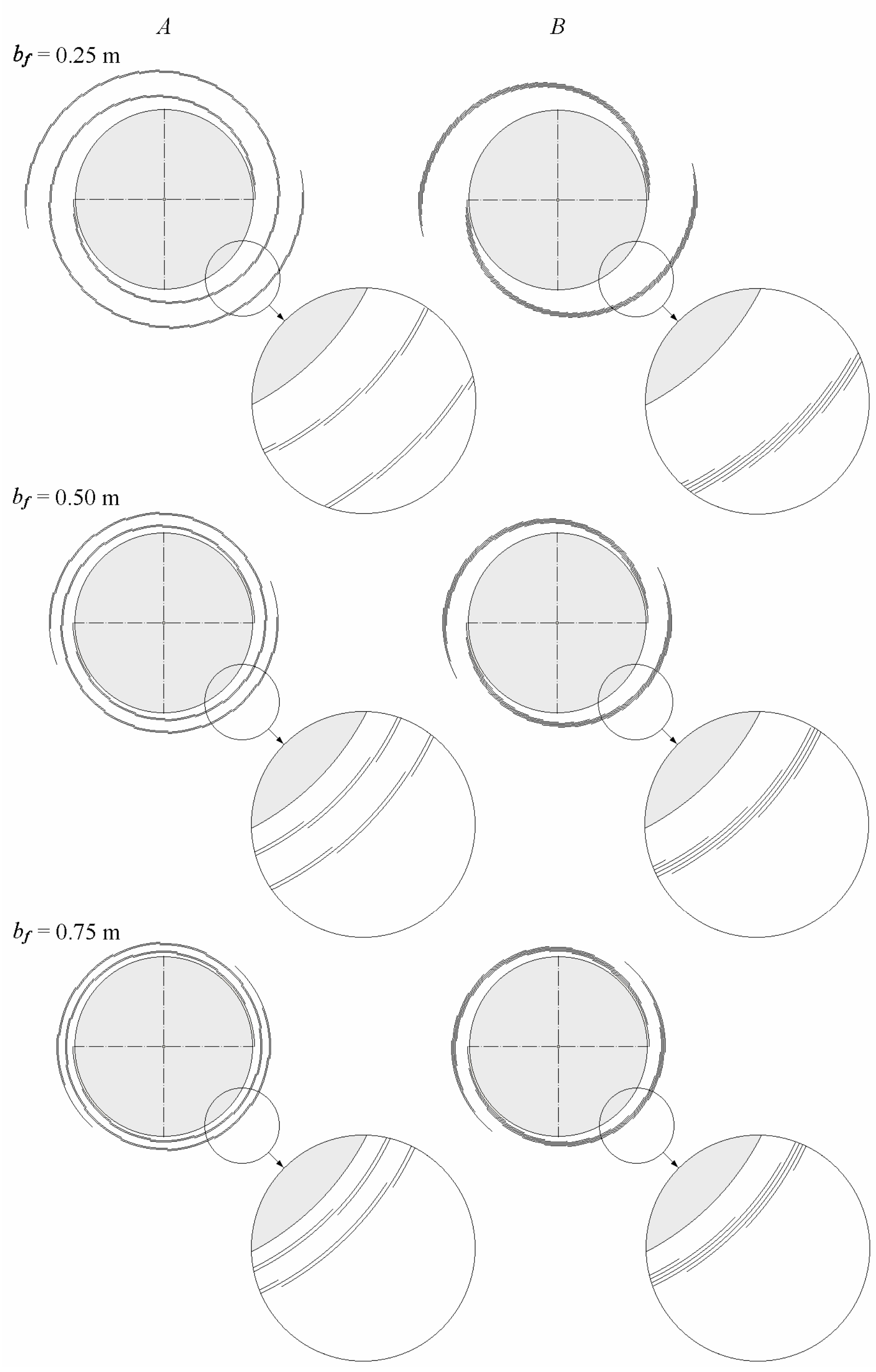

Fig. 4. The geometry of foil strips distribution in the bale's cross-section for the variants considered

DISCUSSION AND CONCLUSIONS

When using overlaps equal to 50% and 75% of the foil width (variants *A* and *B*), the required four layers are obtained and, as a result of applying the final foil strip, over 3% bale's covering of five foil layers is obtained. With the application of variant *A* one rotation about the bale axis is required, and with the application of variant *B* only half of such rotation guarantees the same number of wrappings. The courses of the length and surface area of foil taken from the roll are identical for both variants, which allows us to claim that the consumption of foil and the percentage shares of the numbers of layers are the same. Sawtooth waves of foil surface area as a function of foil width considered result from the variable and non integer value of the ratio of bale's perimeter to foil width, reduced by the value of overlap, which involves the necessity of applying the final supplementary wrapping. This also explains the increased consumption of foil in variant *B* for foil with the width of 0.75.

In general, foil width has no influence on its consumption. While foil width increases, the number of necessary wrappings decreases, and as a result the wrapping time decreases, too. The application of overlap of 75% of the foil width, half-rotation around the bale's axis and wider foil allows to obtain advantageous distribution of layers and much shorter wrapping duration time.

In the case of minimal reduction of foil width, e.g. as a result of applying higher stretching force or in the case of bale skidding during rotation, the number of layers may be lower than the computed according to the algorithm proposed. When using variant *A*, narrow "strips" are created on the bale's lateral surface, which are protected only by two layers, and when using variant *B* – by three layers. In view of the above, in order to obtain the assumed number of layers, overlaps larger than 50% and 75% for variants *A* and *B*, respectively, should be applied. It is recommended to distribute the resulting excess on all overlaps uniformly, which requires a respective program for the control of wrapper motors.

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