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ANALYSIS OF A GRAIN MOTION IN THE TRANSFER AREA OF THE BELT CONVEYOR

ANALIZA RUCHU ZIARNA W PRZESTRZENI PRZESYPOWEJ PRZENOŚNIKA TAŚMOWEGO*

Transfer chutes are critical areas within conveyor transfer systems in terms of maintenance and high levels of energy consumption. Appropriate chute design allows material stream to be uniformly fed on the receiving conveyor with a desired stable tangential speed. This reduces the motion resistances and belt wear. Any construction work associated with a transfer chute should be preceded by a thorough analysis of the stream trajectory. The simplest case is to consider the motion of a single grain. The article presents an analysis of grain motion in a parallel chute and a methodology of calculating the impact angle and tangential speed of the grain at the point of contact with the receiving conveyor belt. Based on calculations made on developed model it was determined which of the basic input parameters have the most significant impact on the changes of observed output parameters.

Keywords: *maintenance of belt conveyors, transfer stations, grain motion analysis.*

Przenośnikowe węzły przesypowe są miejscami newralgicznymi z punktu widzenia eksploatacji jak również energochłonności systemów transportowych. Odpowiednie ukształtowanie konstrukcji przesypu, pozwala na podawanie strugi transportowanego urobku na przenośnik odbierający w sposób równomierny, stabilny i z pożądaną prędkością styczną. Dzięki temu zmniejszane są opory ruchu w przesypie, jak również zużycie taśmy. Prace konstrukcyjne związane z zabudową przesypu, powinny być poprzedzone gruntowną analizą trajektorii ruchu strugi. Najprostszym przypadkiem do rozpatrzenia jest ruch pojedynczego ziarna. W artykule przedstawiono analizę ruchu ziarna w przesypie równoległym oraz metodykę obliczeń kątów padania jak również prędkości stycznych ziarna w miejscu jego upadku na taśmę przenośnika odbierającego. Na podstawie obliczeń modelowych określono, które z podstawowych parametrów przesypu mają najistotniejszy wpływ na zmiany obserwowanych wielkości.

Słowa kluczowe: *eksploatacja przenośników taśmowych, przesypy, analiza ruchu materiału.*

1. Introduction

Conveyor transport systems are based mainly on conveyor belts, which are basic and universal means of transport of particulate materials. The structure of such systems can vary and usually consists of a few or several conveyors connected together with so called transfer chutes, where the transported material is directed from the feed conveyor onto the receiving one. These are usually critical places a source of dust and rapid energy transformations and require special attention from the designer, because a poorly designed chute may be the cause of costly failures and downtime. If a material stream is not fed tangentially from the feed conveyor to the receiving conveyor at a speed equal to the speed of the belt, there is a further increases of resistances and power consumption in the transfer point. In case of feeding a material stream with capacity Q [t/h] perpendicular to the receiving conveyor belt with the speed v [m/s], the resistance value is [1, 5, 10]:

$$W_z = \frac{Q \cdot v}{3,6} \quad [\mathrm{N}] \qquad (1)$$

and the loss of power due to energy transformations

$$N_z = W_z \cdot v = \frac{Q \cdot v^2}{3,6} \quad [\mathrm{W}] \qquad (2)$$

For example, for capacity $Q_{1\text{-}3}$ = 1000-3000-5000 [t/h] and belt speed v=1÷6 [m/s] results are shown at fig. 1.

From these data, it appears that the additional resistance and power dissipation for a single transfer chute can be significant, and it increases proportionally with a growing number of transfer chutes.

a)

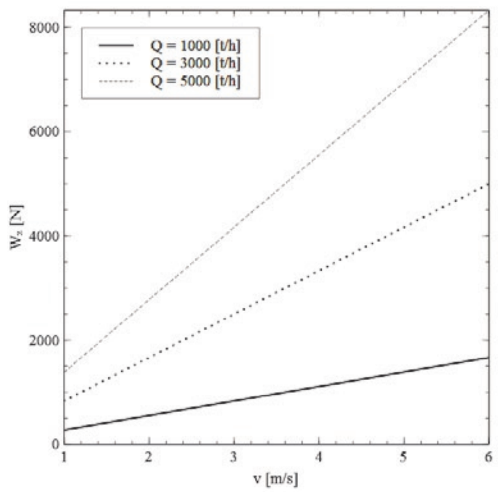


Fig. 1a. A graph of $W_z(v)$

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** b)

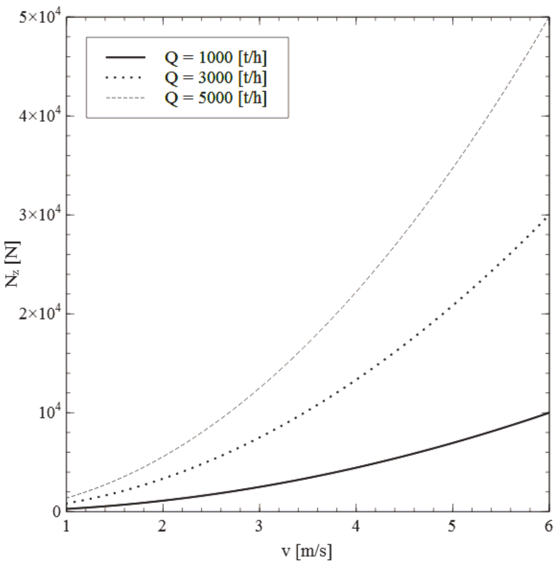


Fig. 1b. Graph of: $N_z(v)$

In order to reduce the energy consumption of conveyor transport systems there is a need to look for better solutions of transfer chutes based on the analysis of construction and operation of previously used ones.

In this paper, the construction of typical transfer chutes is presented and analysis of the effect of geometrical and kinematic parameters of the chute on the grain motion and impact on the receiving conveyor belt was performed. These parameters have a significant influence on additional resistance, lost power and wear of the chute components as well as the belt life, so proper values are essential for the rational design of transfer points.

2. Construction of transfer chutes in conveyor transport systems

Conventional transfer chute design is relatively simple (figures 2–5). Fundamentally, standard steel sections and plates are used with additional removable linings made of other materials which acts as protection against wear. The correct combination and configuration of the above, as well as their geometric configuration and selection of construction materials determines the functionality of the solution. The transfer stations are also often equipped with various types of devices for measurement and control of the flow of material.

General scheme of a typical transfer station area is shown on Figure 2. It can be divided into the following four characteristic zones [9].

A. *Head chute* – space surrounding the front drum of a feed conveyor; at this point the separation of the material from the belt occurs and, depending on the design, free flight of a certain trajectory or capturing the material stream by chute components (such as impact plates).

B. *Free flight area* – an area in which the material falls freely, without contact with the elements of the chute; if the stream is dispersed, depending on how it was captured in zone A, a significant amount of air gets into it, which in turn leads to the formation and emission of dust.

C. *Loading chute* – the area where the material is getting in contact with the receiving conveyor belt; there may be elements of the lower intercept (chutes, slides), or is loaded directly to belt (within the hopper).

D. *Stream formation* – in this area loaded material stream is being formed to its final shape/cross section; it is very often equipped with de-deusting devices. The movement of material during loading is usually turbulent and in this area should be stabilized.

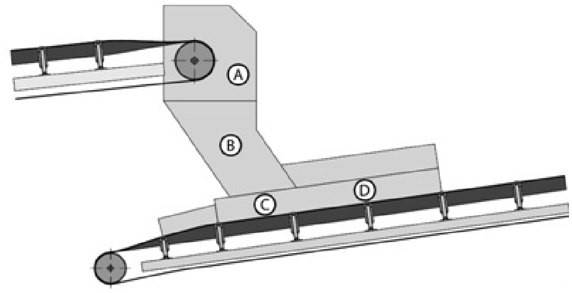


Fig 2. General construction of typical transfer chute with indicated characteristic zones [9]

Depending on the requirements determined by the process and the properties of transported materials, structures of transfer chutes differs. The simplest classification can be division into transfer points, in which the direction of motion of the material stream changes (angle chutes), or remains the same (parallel chutes). Examples of such transfers are shown on figure 3. The whole transfer point contains many elements and devices, whose job is to direct the stream of transported material in such a way as to minimize the negative effects that occur during handling (additional resistance, increased belt wear, noise, etc.).

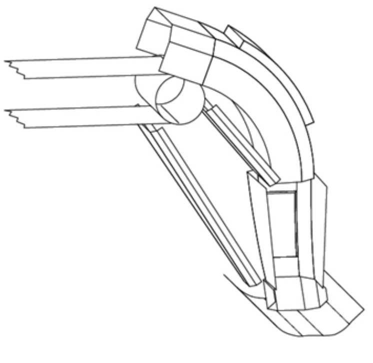
a)

b)

Fig. 3. View of a transfer chutes: a) parallel; b) angeled [7]

Depending on the difference in height between the conveyors, and their arrangement, various kinds of components are used in aim to capture and redirect the stream. The three most commonly used solutions are: impact plate, chutes (straight or curved) and so called “rock box”, which are specially shaped pockets being filled by the material and after that stream reflects from successive layers of accumulated heap. Typical chute structures are based on combinations of these elements. Terminology for structural elements is very diverse, there are many different authors who refer to the same components using different names.

a)



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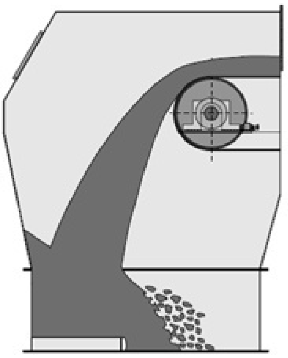

Fig. 4. Angled transfer point with straight and curved chutes (left) and a rock box construction (right)

The use of individual solutions is largely determined by physico-mechanical properties of the material: the size and hardness of solids, the degree of abrasiveness, the degree of moisture. Two commonly used solutions are transfer points of type impact plate to impact plate and impact plate to rock box [8]. In both cases, the stream of material is artificially and suddenly disturbed, which can lead to many problems in maintenance. These systems behaves well in transport of free flowing dry materials. Selection criteria are based mainly on two aspects: blocking of the chute and wear of its components and receiving belt [4]. Recently the new type of construction, composed of curved chutes in capturing and loading zones, called Hood-and-Spoon is beginning to be widely used. It exhibits several advantages especially when material is sticky and cohesive. However, it is more costly than the traditional design and is not so well recognized in practice.

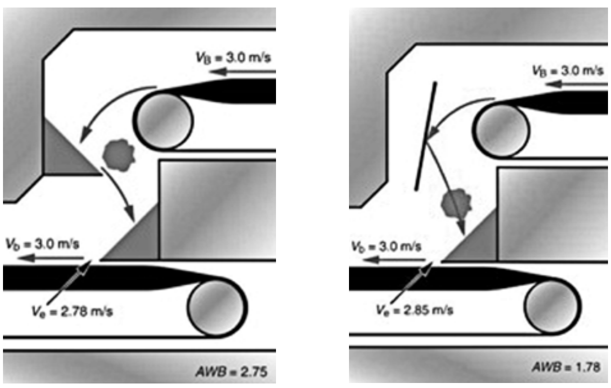

Fig. 5. Schemes of rock box to rock box transfer (left) and impact plate to rock box (right) [8]

Currently, more attention is paid to energy efficiency in the construction of transport machines and equipment is shown at figure 6. Motion of a single grain of diameter a was investigated. The aim was to determine the impact of changes in various parameters on the system response. In particular, the object of interest were the normal and tangential components of the velocity of grain in point of impact on the receiving conveyor belt.

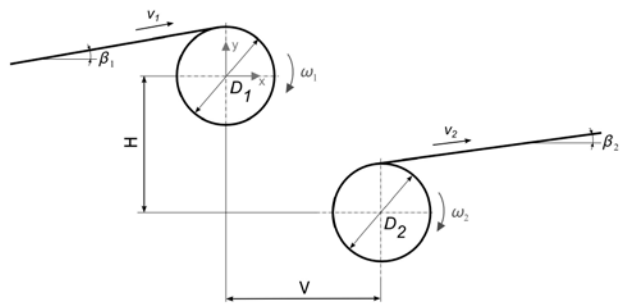

Fig. 6. Belt conveyors in parallel configuration

Input parameters:

v_1, v_2 – belt speeds [m/s],
β_1, β_2 – conveyors inclination [deg],
ω_1, ω_2 – angular speeds of head drums [rad/s],
H, V – horizontal and vertical distance from drums axis [m],
D_1, D_2 – drums diameters [m],
h_1, h_2 – belt thickness [m],
a – grain diameter [m].

where: $v_i = \omega_i \cdot R_i$ and $R_i = \frac{D_i}{2}$ for $i = 1,2$.

Several methods for trajectory calculation exist (Dunlop, Goodyear, CEMA, MHEA, Booth, Korzeń). The differences are mainly due to the range of physical phenomena included, which are affecting the forces acting on the grain. These methods can be divided into three categories: analytical, graphical or combined. In each of the methods it is needed to determine the point of separation of the grain from the feed conveyor belt. The analysis conducted by the authors was based on the formulas derived in the standard CEMA (Conveyor Equipment Manufacturers [4]). The calculations take into account the effect of centrifugal force, but does not take into account the friction and adhesion forces between the belt and the grain. Three cases are considered depending on the angle of inclination of the feed conveyor:

1. $\beta_1 = 0$

1.1. If $\frac{v_s^2}{g \cdot r_1} \geq 1$, grain will separate at the point of contact between the belt and head drum. Assuming that the origin is coincident with the axis of the drum, the coordinates of the point of separation for this case are $x_0 = 0$ and $y_0 = 0$.

1.2. If $\frac{v_s^2}{g \cdot r_1} < 1$, the grain before separation will traverse a certain distance around the head drum until $\frac{v_s^2}{g \cdot r_1} = \cos\gamma$, where is the angle between the vertical axis of the drum, and the point of separation of the grain. The coordinates of the point of separation for this case are $x_o = r_1 \cdot \sin\gamma$ and $y_o = r_1 \cdot \cos\gamma$ wherein $\gamma = \arccos(\frac{v_s^2}{g \cdot r_1})$.

2. $\beta_1 > 0$

2.1. If $\frac{v_s^2}{g \cdot r_1} \geq 1$, grain will separate at the point of contact between the belt and head drum. Taking into account the inclination of the conveyor, the coordinates of the point of separation for this case are $x_o = -r_1 \cdot \sin\beta_1$ and $y_o = r_1 \cdot \cos\beta_1$

2.2. If $\frac{v_s^2}{g \cdot r_1} < 1$ and , grain may separate at the point of contact between the belt and head drum, however, it is likely that it will come in contact with the belt again. It is not clearly stated how to determine the point of separation. CEMA suggests that the grain after contact with the belt will travel some distance around the drum, and then the separation occurs (see p. 2.4).

2.3. If $\frac{v_s^2}{g \cdot r_1} = 1$, the grain will separate at point with coordinates $x_o = 0$ and $y_o = r_1$.

2.4. If $\frac{v_s^2}{g \cdot r_1} < \cos\beta_1$, the grain remains on the belt and will travel some distance around the head drum, to the point in which the condition $\frac{v_s^2}{g \cdot r_1} < \cos\gamma$ is satisfied . The model assumes that the separation occurs when the $\frac{v_s^2}{g \cdot r_1} \geq \cos\gamma$, thus separation point has coordinates $x_o = r_1 \cdot \cos\gamma$ and $x_o = r_1 \cdot \sin\beta_1$.

3. $\beta_1 < 0$

3.1. If $\frac{v_s^2}{g \cdot r_1} \geq \cos\beta_1$, the grain may separate at the initial point of contact between the head drum and belt. This point will have coordinates $x_o = r_1 \cdot \sin\beta_1$ and $y_o = r_1 \cdot \cos\beta_1$.

3.2. If $\frac{v_s^2}{g \cdot r_1} < \cos\beta_1$, the speed v_s is too low for the separation at the initial point of contact between the head drum and belt. The grain remains on the belt and will travel some distance around the head drum, to the point in which the condition $\frac{v_s^2}{g \cdot r_1} \geq \cos\gamma$ is satisfied.

Speed v_s should be calculated taking into account the thickness of the belt h_1 [4] : $v_s = \omega_1 \cdot r_1$; where: $r_1 = R_1 + h_1 + a$.

After separation of the grain, free flight occurs. Air resistance were omitted in the analysis. CEMA method describes the trajectory equation in the coordinate system associated with the point of separation of the grain. From the point of view of positioning components responsible for capturing and directing material stream, it was decided to put the origin at the center of the head drum of feed conveyor. In such coordinate system the equations describing the movement of grain are as follows:

$$x(t) = x_0 + v_s \cdot \cos\theta \cdot t \tag{3}$$

$$y(t) = y_0 + v_s \cdot \sin\theta \cdot t - \frac{g \cdot t^2}{2} \tag{4}$$

where angle θ depending on the inclination angle and speed conditions of the conveyor is equal to β_1 or γ. By removing time from the above equations, trajectory of a grain in the xy plane is described:

$$y(x) = y_0 + (x - x_0) \cdot tg\theta - \frac{g}{2} \cdot \left(\frac{x - x_0}{v_s \cdot \cos\theta} \right)^2 \tag{5}$$

Belt of the receiving conveyor was treated as perfectly rigid and inflexible. With these assumptions, it can be mathematically described as a line equation:

$$y_2(x) = tg\beta_2 \cdot x + b \tag{6}$$

The value of the parameter *b* was calculated based on knowledge of the point of tangency of the belt and drum

$$x_e = V - r_2 \cdot \sin\beta_2 \tag{7}$$

$$y_e = r_2 \cdot \cos\beta_2 - H \tag{8}$$

where: $r_2 = R + h_2$

Based on equations (6), (7) i (8) was derived:

$$r_2 \cdot \cos\beta_2 - H = tg\beta_2 \cdot (V - r_2 \cdot \sin\beta_2) + b \tag{9}$$

so:

$$b = r_2 \cdot \cos\beta_2 - H - tg\beta_2 \cdot (V - r_2 \cdot \sin\beta_2) \tag{10}$$

Finally, the equation describing the belt is given by:

$$y_2(x) = tg\beta_2 \cdot x + r_2 \cdot \cos\beta_2 - H - tg\beta_2 \cdot (V - r_2 \cdot \sin\beta_2) \tag{11}$$

The coordinates of the impact point were calculated by comparing to each other right sides of equations (5) and (11)

$$y(x) = y_2(x) \text{ dla x > 0} \tag{12}$$

$$y_0 + (x - x_0) \cdot tg\theta - \frac{g}{2} \cdot \left(\frac{x - x_0}{v_s \cdot \cos\theta} \right)^2 = tg\beta_2 \cdot x + b \tag{13}$$

arranging the equation (13):

$$\sigma \cdot x^2 + C_1 \cdot x + C_2 = 0 \tag{14}$$

where:

$$\sigma = \frac{g}{2 \cdot v_s^{\,2} \cdot \cos^2 \theta} \tag{15}$$

$$C_1 = tg\beta_2 - 2 \cdot \sigma \cdot x_0 - tg\theta \tag{16}$$

$$C_2 = \sigma \cdot x_0^{\,2} + x_0 \cdot tg\theta + b - y_0 \tag{17}$$

Solving the quadratic equation (12) and taking into account that searched coordinate $x > 0$, we obtain:

$$\Delta = C_1^{\,2} - 4 \cdot \sigma \cdot C_2 \tag{18}$$

$$x_{c1} = \frac{-C_1 - \sqrt{\Delta}}{2 \cdot \sigma} \tag{19}$$

$$x_{c2} = \frac{-C_1 + \sqrt{\Delta}}{2 \cdot \sigma} \tag{20}$$

because $x_{c2} > 0$ it is substituted in the equation (5):

$$y_c = y_0 + (x - x_{c2}) \cdot tg\theta - \frac{g}{2} \cdot \left(\frac{x - x_{c2}}{v_s \cdot \cos\theta} \right)^2 \tag{21}$$

Thus, the point of impact of the grain at the belt of receiving conveyor has the coordinates x_{c2}, y_c. In order to determine the angle of impact of the grain, derivative of the equation of the trajectory with respect to x has to be calculated:

$$\frac{dy}{dx} = -2 \cdot \sigma \cdot (x - x_0) + tg\theta \tag{22}$$

Calculating value of the derivative at point $x = x_{c2}$ we get:

$$\left(\frac{dy}{dx} \right)_{x = x_{c2}} = -2 \cdot \sigma \cdot (x_{c2} - x_0) + tg\theta = tg\alpha \tag{23}$$

where: α - angle of impact in the global coordinate system
hence:

$$\alpha = arctg[-2 \cdot \sigma \cdot (x_{c2} - x_0) + tg\theta] \tag{24}$$

Total impact angle is a sum of α and β_2 (rys.7).

In the coordinate system associated with the center of the drum of a feed conveyor, velocity components of the grain at the point of contact with the belt of receiving conveyor are described by equations:

$$v_x = v_s \cdot \cos\theta \tag{25}$$

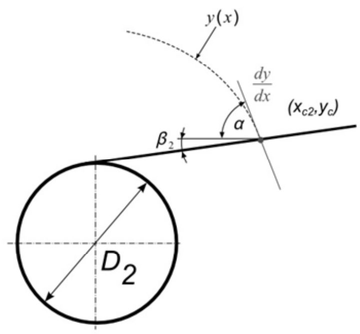

Fig. 7. Angle of impact of the grain on the belt of receiving conveyor

$$v_y = v_s \cdot \sin\theta - g t_c^{\,2} \tag{26}$$

where:

$$t_c = \frac{x_{c2}}{v_s \cdot \cos\theta} \tag{27}$$

Magnitude of velocity vector is:

$$v = \sqrt{v_x^{\,2} + v_y^{\,2}} \tag{28}$$

In the analysis, values of the velocity vector in the direction of the normal and tangential to the receiving conveyor belt were of interest. Given the inclination angle of the second conveyor, the angle of impact of the grain and its velocity components in global coordinate system at the moment of impact, values of velocity components normal and tangent to the receiving belt were calculated from:

$$v_n = v \cdot \sin(\alpha + \beta_2) \tag{29}$$

$$v_t = v \cdot \cos(\alpha + \beta_2) \tag{30}$$

4. Sensitivity analysis of the model

System was analyzed in terms of the influence of selected parameters on the value of the tangential velocity at the moment of impact of the grain on receiving conveyor belt. Following input parameters were chosen: inclination angels β_1, β_2, feed conveyor speed v_1 and horizontal distance H. Each of the factors was analyzed on two levels and results are shown on figures 8 and 9.

Table 1. The values of chosen transfer chute parameters

Parameter	min (-1)	max (+1)
v_1 [m/s]	1	3
β_1 [deg]	−15	15
β_2 [deg]	−15	15
H [m]	1	4

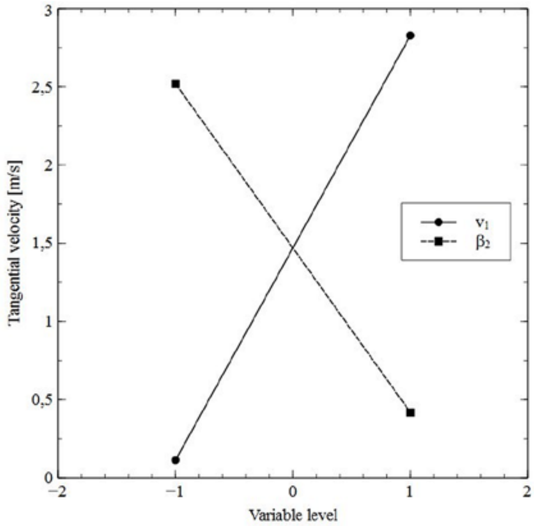

Fig. 8. Mean change in tangential velocity v_t depending on v_1 and β_2

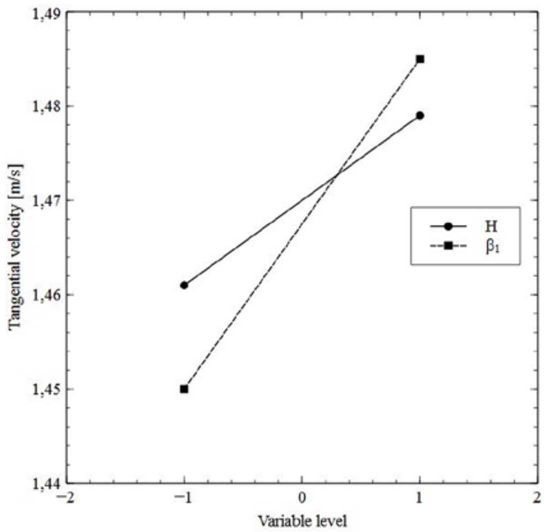

Fig. 9. Mean change in tangential velocity v_t depending on β_1 and H

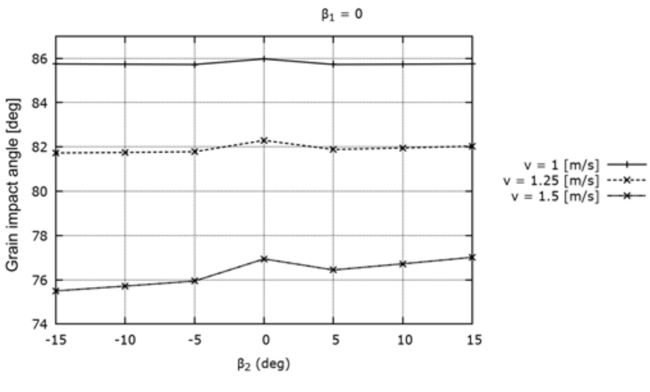

Fig. 10. Angle of impact of a grain depending on v_1 and β_2 for a constant value of β_1= 0°

The results showed that the predominant effects on the tangential velocity of grain at the point of its impact on the receiving conveyor belt are inclination of the second conveyor β_2 and the feed conveyor speed v_1.

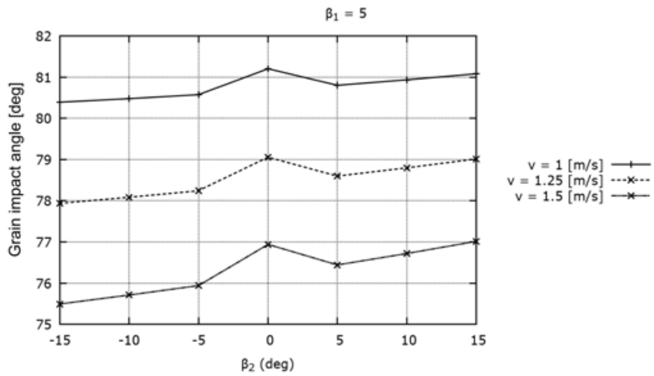

Fig. 11. Angle of impact of a grain depending on v_1 and β_2 for a constant value of β_1= 5°

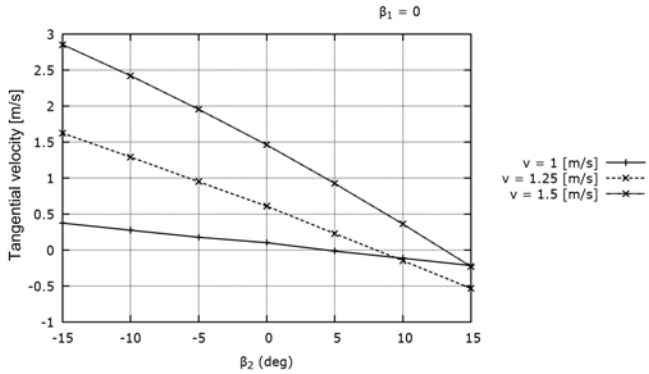

Fig. 12. Tangential velocity at the point of contact depending on v_1 and β_2 for a constant value of β_1= 0°

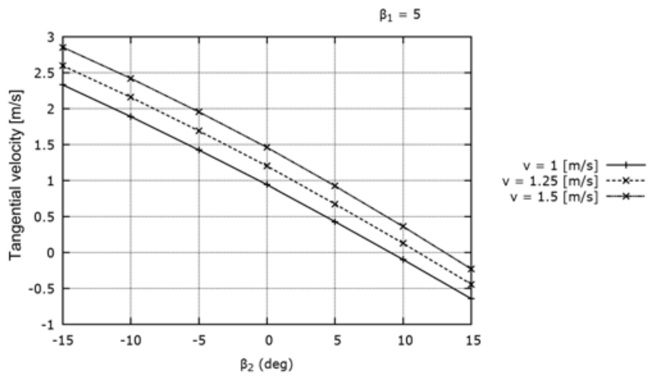

Fig. 13. Tangential velocity at the point of contact depending on v_1 and β_2 for a constant value of β_1= 5°

5. Examples of calculations

Based on the obtained in section 3 relationships, series of calculations were carried out. Speed and impact angle of the grain were determined for a selected range of parameter values β_1, β_2, v_1, H . Other model input parameters were constant. Sample results are shown in the figures 10–13.

Based on the results of calculations, conclusions on the desired configuration of conveyors to achieve favorable conditions for stream loading may be obtained.

6. Summary

In order to improve the efficiency of conveyor transport systems, components and conveyor assemblies are constantly being improved in terms of their adaptation to the growing transport requirements and a multi-action tasks are taken to reduce their energy intensity by reducing the resistance to motion. Transfer stations are one of the key areas of conveyor transport systems which adds considerable resistance and loss of power and a potential source of failure and increased wear of belts. Optimization of chute construction is an actual and important problem to solve. Parameters obtained from the theoretical analysis of the grain motion can be useful in shaping the design elements for eliminating or reducing their defects. Knowledge of the trajectory of the material stream allows for/the proper shaping and design of transfer station construction. These issues will be the subject of further research and construction design work carried out in this area.

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