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GENERAL MODEL OF SILO DISCHARGE OPERATED BY A PNEUMATIC ACTUATOR

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Abstract: Special characterisations of bulk materials cannot be taken into account in traditional dimensioning methods. The aim of this paper to show our research to develop a general model for the discharging process of bulk solids which involves more elements of the discharging process neglected before. Using more suitable equipment can result the reduction of the discharging time which can improve the productivity, the stress of the discharging devices caused by the uncontrolled mass and the cost of the structure caused by the over-dimensioning. The developed model is suitable to make numerical computer methods and software to calculate the operation parameters of the discharging process of bulk solids.

Keywords: silo, dosing of bulk solids, modelling, pneumatic operation

1. Introduction

Nowadays the technical level of industrial processes is very high because of the strong development of technical methods. It can be said that the general technical development reaches a level from where the further increasing is very hard. Exceptions are only the basically new technologies and methods, but their applicability are limited to certain fields. Taking the above mentioned facts into consideration there is one real possibility to increase the efficiency of the industrial processes which is the maximization of the exploitage of the available capacities.

In the most cases it means that the operation of the applied equipment have to be supervised and new dimensioning methods have to be applied which cannot be used before because of their complexity and application problems. There is a good example for this tendency the increasing application of computer simulations and numeric calculation methods (FEM, DEM, etc.).

In accordance with the above mentioned tendencies and the special characterisations of bulk materials which cannot be taken into account in traditional dimensioning methods, the aim of our research to develop a general model for the discharging process of bulk solids which involves more elements of the discharging process neglected before.

2. Discharging of bulk materials

Discharging process of bulk solids means the delivery process of a measured quantity of bulk material between a transportation device or storage equipment and another device or a technology element in bulk form.

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In traditional discharging processes separation of the required quantity is actualized by two different devices: a discharging and a measuring (by mass or volume) equipment. As the accuracy of the dosing process depend on the measuring device, the operation of the discharging device is not optimized, which means that in generally the characterisation and the behaviour is not known. So the negative effects came from this equipment cannot be analysed during the design process.

Dimensioning of a discharging process operated by a pneumatic actuator is in generally actualised based on experimental methods. Therefore this dosing accuracy cannot be suitable for those industrial processes where the quantity of the product determined by the exact quantity of the raw materials (for example glass production). To increase the accuracy new, better dimensioning methods are required which can be developed based on the general model of the discharging process.

In the practice discharging processes and their equipment can be very different in the aspect of structure, operation, application surrounding and specification, size and procedure. Of course, the principals are the same, but the actualisation particularly depends on the materials and the applications. Characterisations and forms of the differences have large effects on the design and operation process of a given discharging task, so general method for the discharging process cannot be described.

Taking the above mentioned facts into consideration we selected some given discharging devices, a bulk solid type and a given silo structure as the target of our research. Of course the definition of the structure limits the applicability of the model, but the results can be used for the given cases without restrictions.

3. Elements of the dosing process

To describe the discharging process a general model required which defines the process elements and their relations. In case of a direct, discontinuous dosing process, vertical outflowing and double segment discharging device operated by a pneumatic actuator, the main, influencing elements of the dosing process are the pneumatic cylinder, the discharged bulk material, the silo structure and the discharging device.

The above mentioned elements belong to three individual technical fields, so to describe the general model of the dosing process we have to know the details of the required elements, which are

- pneumatics (describe the movement of the actuator),
- mechanics of the bulk solids (stresses and outflowing),
- materials handling (discharging solutions).

3.1. Operation of pneumatic cylinders. To determine the operation parameters of pneumatic actuators we need to know the characterisations of the air and need to use the equations described its thermodynamic and hydrodynamic behaviour. The differential-equation system of pneumatic actuators is well known in the literature from ages [1], but it cannot be solved analytically because of the complexity of the relations.

There is another way to solve the differential-equation system, we have to use numerical methods, for which a special model contains the operation phases of the pneumatic actuator has to be used.

The operation phases of a double acted pneumatic cylinder with linear piston and cushioning are:

1. Starting operation without movement (chambers are filled or vented)
2. Normal movement of the piston:
    a. acceleration
    b. moving with constant velocity
3. Cushioned movement,
4. Finishing operation without movement (chambers are filled or vented)

The individual operation phases are activated in certain states of the parameters, which can be defined in phase-changing conditions (Fig. 1).

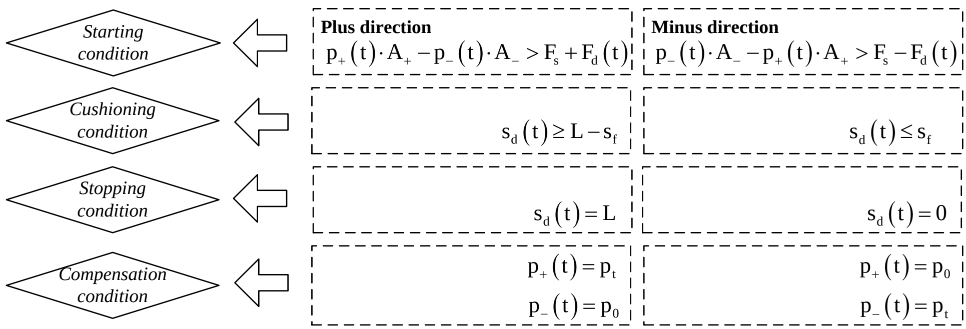

Figure 1. Phase changing conditions of the pneumatic cylinder

The equations of the differential-equation system of the actuator are the same in Phase 1. and 4. (Fig. 2.), the differences are only the outflowing cross section and the piston surface in the minus chamber.

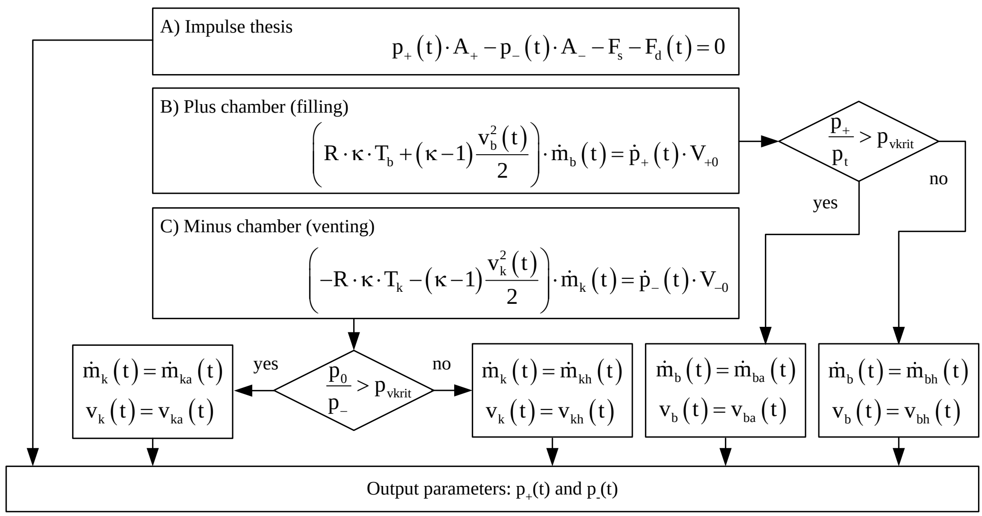

Figure 2. Equations in Phase 1 and 4 (in plus direction)

The form of the impulse thesis has not got any effect to the pressure in the chambers, it only determines the starting condition.

The equations of the differential-equation system are also the same in Phase 2 and 3 (Fig. 3.), and the differences are also the same as in Phase 1 and 4. Further difference is that the acceleration of the piston in Phase 2.a. is a variable value, but in Phase 2.b. it is always zero.

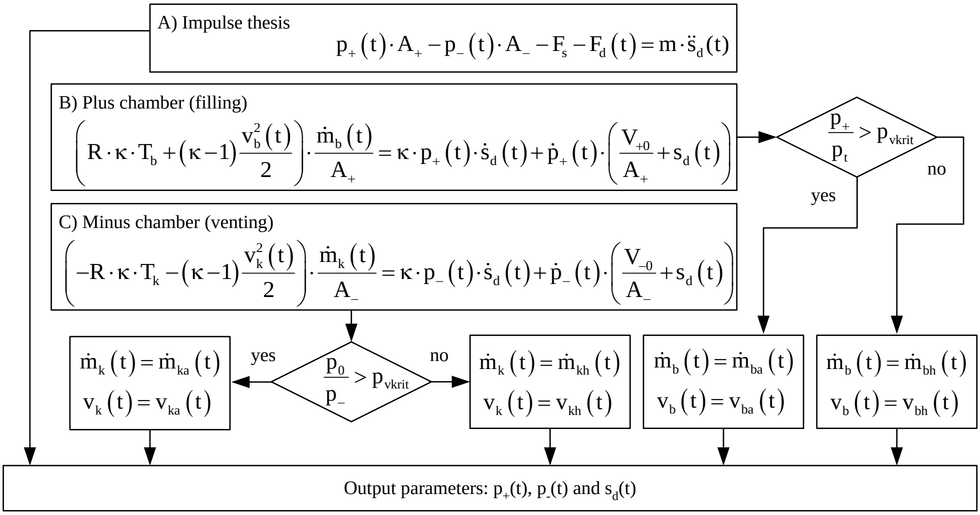

Figure 3. Equations in Phase 2 and 3 (in plus direction)

In minus direction (when the piston rod is going into the cylinder) the equations are the same as in plus direction, but the pressure values change their places (the plus chamber is filled, and the other is vented).

3.2. Parameters of bulk materials. There are different methods in the literature to describe the behaviour of bulk solids, which give different solutions for the determination of the relation of the particles. In the model of the discharging process in the aspect of stresses we used the basic Janssen method for the static state [2] and another method for the flowing state [3] which is also based on the Janssen principle.

Because of the large differences between the individual bulk material types, the model of the discharging process is valid only for a given material type (grained, free flowing, non-cohesive and homogenous bulk materials).

3.3. Operation of discharging devices. The structure of the discharging device has significant effect to the discharging process. It determines

- the relation between the movement of the piston of the pneumatic actuator and the discharging device,
- the size and characterisation of the load acted on the piston from the bulk solid,
- the shape and size of the real outflowing gap.

Taking the above mentioned effects into consideration, it has to be described the relations between the movement of the piston and the material surfaces which are opened or closed by the discharging device [4]. These relations can be different at the usable discharging device types, which are in generally shutters or double-segment gates.

4. General model of the dosing process

After the determination of the process elements and their relations the general model of the discharging process can be described. The model contains the operation phases of the pneumatic actuator and the discharging phases (Fig. 4.).

If the discharging device moves only during the normal movement of the piston (Phase 2.), the dynamic effects of the cushioned movement to the dosed material quantity can be avoided. With the suitable structure of the discharging device this situation is easily available.

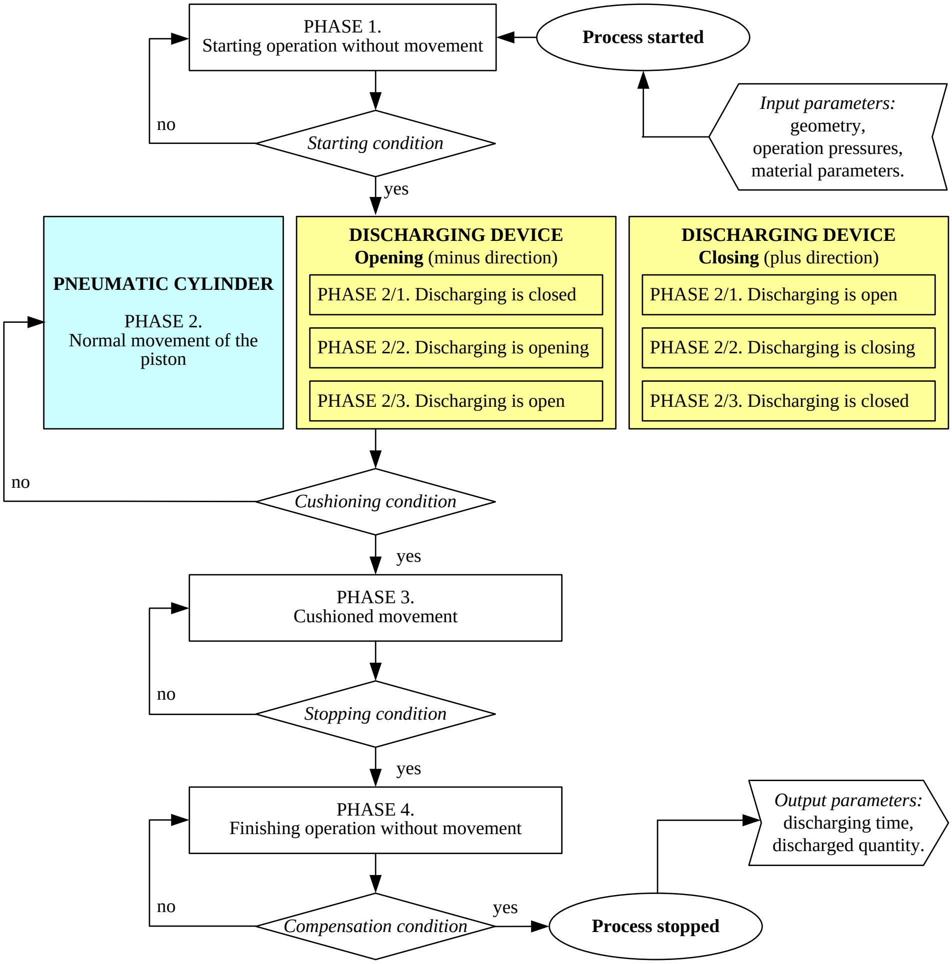

Figure 4. General model of the dosing process

To determine the phases of the discharging further conditions are required suited to the movement of the device for the opening and the closing process. Sub phases of the discharging process are the opening, the opened state and the closing.

To determine the states of the discharging process some more phase changing conditions are required, which are

- opening condition (opening),
- maximum outflow condition (opening),
- closing condition (closing),
- zero outflow condition (closing).

For Phase 2. the opening and also the closing process has to be described, because the steps and the applied conditions of the process are different (Fig. 5. and 6.). The equations of the material flowing are the same in the opening (Fig. 5.) and the closing (Fig. 6.) process, but the phases are exchanged and the conditions are modified. The opening, closing, maximum and zero conditions (see in Fig. 5. and 6.) are valid only for symmetric operation.

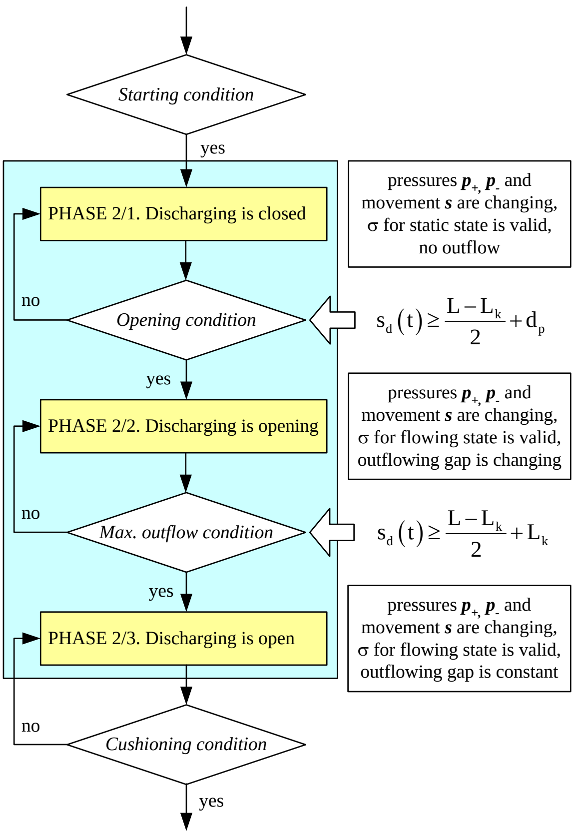

Figure 5. Model of the discharging during opening

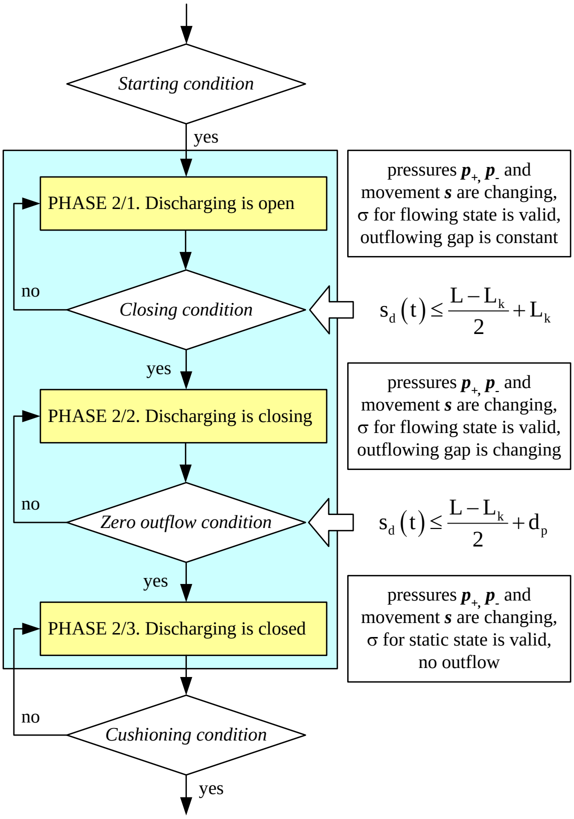

Figure 6. Model of the discharging during closing

The equations of the material flowing are the same in Phase 2.1. of the opening and in Phase 2.3. of the closing (Fig. 7.).

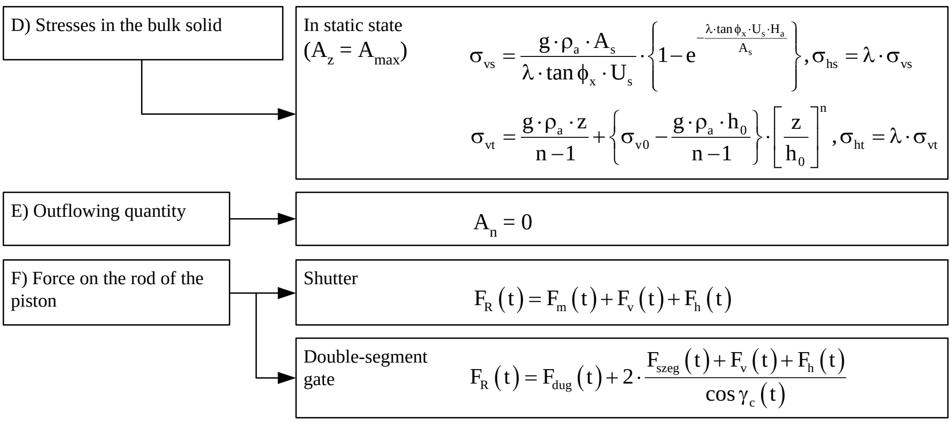

Figure 7. Equations in Phase 2.1 during the opening and in Phase 2.3 during the closing

The equations of the material flowing are the same in Phase 2.2 and 2.3 during opening and in Phase 2.1. and 2.2. during closing (Fig. 8.), The difference is only the size of the discharging gap.

D) Stresses in the bulk solid	During outflowing $A_z = A_z(t)$	$\sigma_m = \left(1 - e^{\frac{-2 \cdot h \cdot U_k}{A_k \cdot (c_a + c_b)}}\right) \cdot \left(\frac{A_k}{2 \cdot U_k} \cdot \rho_a \cdot g \cdot (c_a + c_b)\right)$
E) Outflowing quantity $A_n = A_n(t)$	Janssen	$\dot{m}_a = A_k \cdot \rho_a \cdot \nu \cdot \sqrt{\left(1 - e^{\frac{-2 \cdot h \cdot U_k}{A_k \cdot (c_a + c_b)}}\right) \cdot \frac{A_k}{U_k} \cdot g \cdot (c_a + c_b)}$
F) Force on the rod of the piston	Shutter	$F_R(t) = F_m(t) + F_v(t) + F_h(t)$
	Double-segment gate	$F_R(t) = F_{dug}(t) + 2 \cdot \frac{F_{szeg}(t) + F_v(t) + F_h(t)}{\cos \gamma_c(t)}$

Figure 8. Equations in Phase 2.2 and 2.3 during the opening and in Phase 2.1 and 2.2 during the closing

5. Summary

More accurate determination of the parameters (time and quantity) of the discharging process can help to select more suitable discharging equipment for given discharging processes and bulk materials. Using more suitable equipment can result the reduction of the discharging times which can improve the productivity, the stress of the discharging devices caused by the uncontrolled mass and the cost of the structure caused by the over-dimensioning.

As the final result of our research we can say that the developed model and their computer based realization are suitable for design of discharging equipment at these given parameters (small silo, given bulk materials, given opening-closing structures, etc.). The model is suitable to make numerical computer methods and software to calculate the operation parameters (outflowing quantity, opening and closing time, etc.) of the discharging process of bulk solids.

Of course to use this model as a general method we have to make many other tests with new bulk materials, structures and silos. Our next step is the examination of the applicability of the model for new materials which is in progress now.

Another possibility to qualify the applicability of this model is comparing the results to discrete elements methods (DEM). In our department we deal with a DEM software and in a later phase we will make this comparison.

Acknowledgements

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List of symbols

A_+	- surface of the piston in the plus chamber [m^2]
A_-	- surface of the piston in the minus chamber [m^2]
A_k	- discharging cross section [m^2]
A_{max}	- maximal cross section of the discharging gap [m^2]
A_n	- opened surface of the discharging gap [m^2]
A_s	- cross section of the silo [m^2]
A_z	- closed surface of the discharging gap [m^2]
c_a, c_b	- influencing factors depend on the characterisation of the bulk solid [5]
d_p	- average particle diameter of the bulk solid [m]
L_k	- length of the discharging gap (at rectangle shape) [m]
F_d	- total force on the piston from external loads [N]
F_{dug}	- force from the weight of the moving elements of the cylinder [N]
F_h	- force on the closing element from the horizontal pressure of the material [N]
F_m	- force from the weight of moving elements of the cylinder and the shutter [N]
F_R	- force on the piston rod [N]
F_s	- total force on the piston from friction [N]
F_{szeg}	- force from the weight of the closing segment [N]
F_v	- force on the closing element from the vertical pressure of the material [N]
ϕ_x	- coefficient of wall friction [^{o}]
g	- acceleration of gravity [m/s^2]
γ_c	- angle determined by the movement of the segment and the cylinder position [^{o}]
h	- height of the moving bulk material [m]
h_0	- height of the cone (or pyramid) of the hopper [m]
H_a	- height of the bulk material in the silo [m]
κ	- adiabatic coefficient
L	- maximal length of the stroke of the piston [m]
λ	- lateral stress ratio of the bulk material
$\dot{m}_a$	- discharged quantity of the bulk material [kg/s]
$\dot{m}_b$	- quantity of the air flowing into the chambers [kg/s]
$\dot{m}_{ba}$	- quantity of the air flowing into the chambers under sonic speed [kg/s]
$\dot{m}_{bh}$	- quantity of the air flowing into the chambers with sonic speed [kg/s]
$\dot{m}_k$	- quantity of the air flowing out of the chambers [kg/s]
$\dot{m}_{ka}$	- quantity of the air flowing out of the chambers under sonic speed [kg/s]
$\dot{m}_{kh}$	- quantity of the air flowing out of the chambers with sonic speed [kg/s]
n	- influencing factor depend on the material and the rigidity of the silo structure [6]
ν	- influencing factor depend on the bulk solid [7]
p_+	- pressure in the plus chamber [Pa]
p_-	- pressure in the minus chamber [Pa]
p_0	- atmospheric pressure [Pa]
p_t	- operating pressure [Pa]
p_{vkrit}	- critical pressure ratio
ρ_a	- bulk density [kg/m^3]
R	- universal gas coefficient [J/(kg·K)]
s_d	- movement of the piston of the pneumatic actuator [m]
s_f	- length of the cushioning [m]
σ_{hs}	- horizontal stress in the silo [Pa]
σ_{ht}	- horizontal stress in the hopper [Pa]

σ_m - vertical stress in the moving bulk material [Pa]
σ_{v0} - vertical stress at the connection line of the silo and the hopper [Pa]
σ_{vs} - vertical stress in the silo [Pa]
σ_{vt} - vertical stress in the hopper [Pa]
T_b - temperature of the air flowing into the chambers [K]
T_k - temperature of the air flowing out of the chambers [K]
U_k - perimeter of the discharging gap [m]
U_s - perimeter of the silo [m]
v_b - velocity of the air flowing into the chambers [m/s]
v_{ba} - velocity of the air flowing into the chambers under sonic speed [m/s]
v_{bh} - sonic speed of the air flowing into the chambers [m/s]
v_k - velocity of the air flowing out of the chambers [m/s]
v_{ka} - velocity of the air flowing out of the chambers under sonic speed [m/s]
v_{kh} - sonic speed of the air flowing out of the chambers [m/s]
V_{+0} - minimum volume of the plus chamber [m^3]
V_{-0} - minimum volume of the minus chamber [m^3]
z - vertical coordinate in the hopper [m] [6]

References

[1] Elek, I.; Hudáky, J.: *Az ipari pneumatika alapjai.* Interpress, Budapest 1979.
[2] Janssen, H. A.: *Getreidedruck in Silozellen.* Zeitschr. d. Vereines Deutscher Ingenieure 39. pp. 1045-1049, 1895.
[3] Sitkei, Gy.: *A mezőgazdasági anyagok mechanikája.* Akadémiai Kiadó, Budapest, 1981. ISBN 963 05 2673 5
[4] Telek, P.: *Silóelzáró szerkezetek elmozdulása és a működtető pneumatikus munkahenger dugattyújának mozgása közötti kapcsolat meghatározása*. GÉP LVIII. évfolyam 2007/5-6. ISSN 0016-8572 pp. 71-77
[5] Illés, B.; Németh, J.; Telek, P.: *Evaluierung der Berechnungsmethoden zum Austrag von Massenfluss-Silos.* Innovationen gegen die Krise. 14. Fachtagung Schüttgutfördertechnik in Magdeburg, pp. 175-184, Otto-von-Guericke-Universität Magdeburg, 2009.
[6] Schulze, D.: *Untersuchungen zur gegenseitigen Beeinflussung von Silo Austragorgan*. Dissertation, Fakultät für Maschinenbau und Elektrotechnik der Technischen Universität Carolo-Wilhelmina zu Braunschweig, 1991.
[7] Németh, J.: *Ömlesztett-anyagok rakodása és tárolása.* Előadás fóliák. Miskolci Egyetem, 2000. pp. 1-132