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DETERMINATION OF OPTIMUM PARAMETERS IN CONNECTION WITH TRANSPORTATION WITH A GAS STREAM

T. BLICKLE and Mrs. E. BÁTOR

(Research Institute for Technical Chemistry of the Hungarian Academy of Sciences, Veszprém)

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The specific energy consumption, and - by way of this - the expenditure of the transportation of solid, granular material with a gas stream is highly dependent on the dimensions of the transport conduit and on the working parameters. If the output of the transport system is given, the diameter of the conduit and the amount of transporting gas has to be chosen so as to obtain minimum transportation costs. This problem was solved by the introduction of intermediate variables. A method of calculation is proposed for the determination of the optimum values of the process parameters, such as gas flow rate and volume ratio of solid. The application of the method is illustrated with the example of vertical transportation of sodium bicarbonate.

The way in which problems of transportation - encountered during industrial production - are solved, often contribute in quite a decisive manner to the costs of production. Accordingly, determination of the optimum parameters of the transportation processes applied is closely related to the economic efficiency test of production processes.

Transportation of solid, granular material through pipelines by a gas stream has become more and more popular in almost every branch of industry. The widespread application of this process is explained by its numerous advantages.The dosts of the installation of the device are low,it can be easily automatized, whereby manual labour can be dispensed with and labour expenses are accordingly reduced. A minimum amount of maintenance is necessary, since there are no moving mechanical parts subject to abrasion and the functioning of the apparatus is highly reliable. The space requirement of the transport conduits is moderate, the pattern of the arrangement of the pipeline is practically unlimited and consequently it can easily be installed even in plants that are already in operation. The conduit lines are hygienic and thus they can also be used in food manufacture. In the chemical industry, the main advantage of the method is that it can be combined with other processes, such as heat exchange, drying, and regeneration of a catalyst, etc. A production process can be made more economical by a combination of such operations.

There is in effect only one drawback to transportation with a gas stream and this is its high energy requirement. The latter may be, at an identical output, as high as five times, or even twenty times as high as that of mechanical devices. The scattering of the energy consumption within extremely wide limits provides a clear indication of the major importance of the actual values of the main dimensions and operating parameters.

THE OBJECTIVE FUNCTION AND CHARACTERISTICS TO BE OPTIMALIZED

The economical aim of optimalization is maximum profit or minimum expenses. However, due to the complicated nature of economic and commercial parameters - which may influence profit in a direct way, i.e. independently of the procedure - it seems more simple to search for a minimum expenditure. The latter is influenced by a number of parameters. However, changes in the parameters of a given process influence only the amortization and energy expenses, and accordingly only these two will be considered as a functional aim [1, 2]:

$$N = N_a + N_e \tag{1}$$

When designing a transport device, the sort of material to be transported, the output, and the starting- and end-points of transportation are usually defined by the problem itself. On the other hand, in the case of transportation with a gas stream it is - within certain limits - up to the designer to decide the quantity of the carrier gas and the diameter of the conduit. During optimalization, the particular values of these two independent variables are sought, at which the sum of the amortization and energy expenses - as related to the unit amount of transported material and the unit path lenght of transportation - are minimal.

In the calculation of the amortization cost, the weight of the transport conduit is taken as the basis:

$$N_a = C_a \frac{\gamma_a \pi}{4\ \tau_a G_s} (D_k^2 - D^2) \tag{2}$$

or, expressed with the wall thickness of the conduit:

$$N_a = C_a \frac{\gamma_a \pi}{\tau_a G_s} \delta_a^2 + C_a \frac{\gamma_a \pi \delta_a}{\tau_a G_s} D \tag{3}$$

The cost of energy can be calculated from the pressure drop in the transporting gas:

$$N_e = C_e \frac{\Delta p}{L} \frac{G_g}{\gamma_g G_s} \tag{4}$$

Accordingly, the complete objective function is:

$$N = C_a \frac{\gamma_a \pi}{\tau_a G_s} \delta_a^2 + C_a \frac{\gamma_a \pi \delta_a}{\tau_a G_s} D + C_e \frac{\Delta p}{L} \frac{G_g}{\gamma_g G_s} \tag{5}$$

OPTIMUM VALUES OF THE OPERATIONAL PARAMETERS

The flow characteristics (such as pressure drop, and rate values, etc.) are generally described by the gas flow rate and the volume ratio of the solid. These operational parameters do not appear in the expense function, but they influence the values of the expense terms and at the same time they also depend on the value of the independent variable in the objective function. Accordingly, these parameters will be regarded as intermediate variables.

The relation between the independent and the intermediate variables is the following:

$$G_s = \frac{D^2\pi}{4} \varepsilon_s \gamma_s u_s \tag{6}$$

$$G_g = \frac{D^2\pi}{4} \gamma_g u \tag{7}$$

Considering Equations (6) and (7), Equation (5) can be brought to the following form:

$$N = A_1 + \frac{A_2}{\sqrt{\varepsilon_s u_s}} + A_3 \frac{\Delta p u}{\varepsilon_s u_s} \tag{8}$$

where

$$A_1 = C_a \frac{\gamma_a \pi}{\tau_a G_s} \delta_a^2 \tag{9}$$

$$A_2 = 2\, C_a \frac{\gamma_a \delta_a}{\tau_a} \sqrt{\frac{\pi}{\gamma_s G_s}} \tag{10}$$

$$A_3 = \frac{C_e}{\gamma_s L} \tag{11}$$

The particle flow rate (u_s) and the pressure drop (Δp) are functions of the gas flow rate and the concentration of the solid:

$$u_s = F_1\ (u,\ \varepsilon_s) \tag{12}$$

$$\Delta p/L = F_2\ (u,\ \varepsilon_s) \tag{13}$$

In order to find the optimum of the operational parameters, the extreme value of the objective function (8) according to intermediate variables ε_s and u is found to be:

$$\frac{\partial N}{\partial \varepsilon_s} = -\frac{A_2}{2}\,\frac{\varepsilon_s \dfrac{\partial u_s}{\partial \varepsilon_s} + u_s}{(\varepsilon_s u_s)^{3/2}} + A_3 u\,\frac{\varepsilon_s u_s \dfrac{\partial \Delta p}{\partial \varepsilon_s} - \Delta p\left(\varepsilon_s \dfrac{\partial u_s}{\partial \varepsilon_s} + u_s\right)}{(\varepsilon_s u_s)^2} = 0 \tag{14}$$

After rearrangement and reduction:

$$\frac{A_2}{2\ A_3} = \frac{u}{\sqrt{\varepsilon_s u_s}}\left[\frac{\varepsilon_s u_s \dfrac{\partial \Delta p}{\partial \varepsilon_s}}{\varepsilon_s \dfrac{\partial u_s}{\partial \varepsilon_s} + u_s} - \Delta p\right] \tag{15}$$

or

$$\frac{A_2}{2\ A_3} = \frac{\Delta p u}{\sqrt{\varepsilon_s u_s}}\left[\frac{\dfrac{\partial \ln \Delta p}{\partial \ln \varepsilon_s}}{\dfrac{\partial \ln u_s}{\partial \ln \varepsilon_s} + 1} - 1\right] \tag{16}$$

By application of simpler designations:

$$\frac{\Delta p\ u}{\sqrt{\varepsilon_s u_s}} = \varphi \tag{17}$$

whence we have

$$\frac{A_2}{2\ A_3} = \varphi\left[\frac{1}{\dfrac{\partial \ln \varepsilon_s}{\partial \ln \varphi}\quad \dfrac{\partial \ln u_s}{\partial \ln \varphi}} - \frac{1}{2}\right] \tag{18}$$

The partial derivative of the objective function according to (u) is:

$$\frac{\partial N}{\partial u} = -\frac{A_2}{2}\,\frac{\varepsilon_s \dfrac{\partial u_s}{\partial u}}{(\varepsilon_s u_s)^{3/2}} + A_3 \frac{\left(u \dfrac{\partial \Delta p}{\partial u} + \Delta p\right)\varepsilon_s u_s - \Delta p\, u \varepsilon_s \dfrac{\partial u_s}{\partial u}}{(\varepsilon_s u_s)^2} = 0 \tag{19}$$

After rearrangement we have:

$$\frac{A_2}{2\,A_3} = \frac{\Delta p u}{\sqrt{\varepsilon_s u_s}}\left[\frac{\partial \ln \Delta p}{\partial \ln u_s} + \frac{\partial \ln u}{\partial \ln u_s} - 1\right] \tag{20}$$

Taking Equation (17) into consideration:

$$\frac{A_2}{2\,A_3} = \varphi\left[\frac{\partial \ln \varphi}{\partial \ln u_s} - \frac{1}{2}\right] \tag{21}$$

The optimum value of the two operational parameters can be determined from Equations (16) and (20) or (18) and (21). These Equations also provide information on the internal relation between the optimum values of the concentration and gas flow rate:

$$\frac{\partial \ln \Delta p}{\partial \ln u} + 1 = -\frac{\partial \ln u_s}{\partial \ln \varepsilon_s} \tag{22}$$

Minimum expenditure can be determined for a given transportation assignment if the concrete form of functions (12) and (13) is known, or there are experimental data on the particle flow rate and gas pressure drop as a function of the gas flow rate and solid concentration at the designer's disposal.

Pressure-drop and Rate Relations in Gas-Solid Two-Phase Flow

Due to the flow resistance, the solid granular material brought into the gas stream is accelerated and carried away by the gas stream in the conduit, if the gas flow rate is higher than the terminal free falling velocity of the particles. A gas stream of the flow rate (u_g) carries the solid particles with a free falling velocity of (u_s) this being lower than the former. The relative rate $v = u_g - u_s$ supplies the driving force necessary for transportation. The relative retardation of the material stream alters the composition of the gas-solid mixture in the conduit as compared to the composition of the material fed into the system. As a consequence of collisions and friction occurring during transportation, the solid is slowed down and has to be accelerated again by the gas stream.This continuous rate energy withdrawal manifests itself in a loss in pressure.

The value of the pressure drop is calculated - according to the modern view point - from the equilibrium of forces acting upon one unit volume of the two-phase stream [3-12]. The following simplifications were introduced for the stream of a gas-solid mixture travelling along a straight conduit:

- the flow is stationary and unidimensional,
- the flow rate of the gas and solid along the cross section of the conduit is constant,
- the solid particles are sphere-shaped and of the same size,
- the distribution of the solid material along the cross section of the conduit is uniform,
- the changes in the state of the gas are isothermal.

The equilibrium of the forces acting upon one unit volume of the two-phase stream can be expressed by

$$A\,dp = T_g + T_s + S_g + K \qquad (23)$$

where the individual terms are:

the inertia force of the gas:

$$T_g = \frac{D^2\pi}{4}\,\varepsilon\,\frac{\gamma_g}{g}\,u_g du_g \tag{24}$$

the inertia forces of the solid

$$T_s = \frac{D^2\pi}{4}\,\varepsilon_s\,\frac{\gamma_s}{g}\,u_s du_s \tag{25}$$

the friction forces of the gas:

$$S_g = \frac{D^2\pi}{4}\,\varepsilon\lambda\,\frac{dL}{D}\,\frac{\gamma_g}{2g}\,u_g^2 \tag{26}$$

the force impeding motion of the solid:

$$K = \frac{D^2\pi}{4}\,\gamma_s\varepsilon_s(au_s^2 + b)\ dL \tag{27}$$

The latter term accounts for effects arising from the collision, friction and lifting of the solid particles.

Accordingly, considering Equations (24), (25), (26) and (27), the equilibrium equation (23) will take the form

$$dp = \varepsilon\,\frac{\gamma_g}{g}\,u_g du_g + \varepsilon_s\,\frac{\gamma_s}{g}\,u_s du_s + \varepsilon\,\frac{\lambda}{D}\,\frac{\gamma_g}{2g}\,u_g^2\ dL + \varepsilon_s\gamma_s(au_s^2 + b)\ dL \tag{28}$$

The first term in Equation (28) can be disregarded, if the expansion of the gas stream may be neglected. In the section where the transport is of constant rate, $du_s/dL = 0$ and consequently the second term of Equation (28) may also be neglected. Accordingly, the value of pressure drop in a straight conduit of optional position is

$$\Delta p = \varepsilon \frac{\lambda}{D} \frac{\gamma_g}{2g} u_g^2 L + \varepsilon_s \gamma_s (a u_s^2 + b) L \qquad (29)$$

It must be pointed out that the explanation given for factors a and b in the Equations by various authors differs. According to BARTH and his followers [3-9]

$$a = \frac{\lambda_j}{2 Dg} \qquad (30)$$

$$b = \sin \alpha + \beta_o \cos \alpha \qquad (31)$$

The value of the additional pipe friction coefficient λ_j, as determined by measurement, is generally given as a function of the Froude-number, with the parameters of the transport characteristics. The factor β_o accounts for the work necessary to lift the particles in the case of horizontal transportation.

The motion-retarding force K, in Hungarian literature, based on works by PATTANTYUS [10], PÁPAI [11] and SZÓNYI [12], is considered to be - in addition to the lifting force required in vertical transportation - the result partly of collisions and partly of friction. Assuming the mean of the retaining force originating from collisions in time to be a force that is acting continuously, the following expression is obtained for factor a:

$$a = \frac{k_{1v}}{2g} (1 + C_1 \sin \alpha) \qquad (32)$$

whereas factor b accounts for the vertical lifting of the weight and the friction of the solid material:

$$b = \sin \alpha + k_2 \xi_s \qquad (33)$$

ξ_s is a constant characteristic of the quality of the solid and of the conduit wall.

In addition to the quality of the transported material and the conduit, the values of factors a and b also depend on the concentration of the solid. According to SZŐNYI [12], the k_{1v} collision coefficient included in factor a has - in the case of low solid concentrations ($\varepsilon_s < 0.03$) - a high and practically constant value. The latter decreases with increasing concentration in an exponential manner. The value of the proportionality factor k_2 increases with increasing solid concentration. In a horizontal conduit, the particles whole weight participates in creating a friction force and the value of k_2 tends to 1. A smaller friction force arises, according to experience, in vertical transportation and consequently the value of k_2 can be only a fraction of that encountered in the previous case. In the case of transportation in a dilute stream - especially if the solid particles are elastic - k_2 tends to zero.

The motion equation of the solid material - with the use of the simplifications discussed earlier - can be derived from the equilibrium of the forces acting upon the particles dispersed in one unit volume of the conduit. The resistance of medium - brought about by the relative velocity between the particles and the gas stream - acts as a driving force and this must be in equilibrium with the inertia force of the particles, and the retaining forces originating from friction or/and collision and lifting work:

$$C_h A_h \frac{\gamma_g}{2g} (u_g - u_s)^2 = \frac{D^2\pi}{4} \varepsilon_s \gamma_s dL \left[\frac{u_s}{g} \frac{du_s}{dL} + a u_s^2 + b \right] \qquad (34)$$

Assuming the specific gravity of the gas to be negligible, as compared to that of the solid: $\gamma_s - \gamma_g \approx \gamma_s$, the weight of the solid present in a unit volume can be expressed with the aid of the terminal free falling velocity:

$$\frac{D^2\pi}{4} \varepsilon_s \gamma_s \, dL = C_h A_h \frac{\gamma_g}{2g} v_s^2 \qquad (35)$$

Accordingly, the equation of motion of the solid phase of a two-phase gas-solid system is:

$$\frac{du_s}{dL} = \frac{g}{u_s}\left[\frac{(u_g - u_s)^2}{v_s^2} - au_s^2 - b\right] \tag{36}$$

In the case of the transportation of a stationary rate $du_s/dL = 0$ and by introduction of the gas flow rate as calculated for the empty conduit cross section:

$$u_s = \frac{1}{1 - av_s^2}\left[\frac{u}{\varepsilon} - v_s\sqrt{(1 - av_s^2)b + a\,\frac{u^2}{\varepsilon^2}}\right] \tag{37}$$

VARIATIONS IN THE EXPENDITURE OF TRANSPORTATION IN THE FUNCTION OF OPERATIONAL PARAMETERS

The formation of expenditure and optimum determination is illustred with the example of the vertical transportation of sodium bicarbonate. The characteristics of the material to be transported are as follows:

$d_o = 9 \cdot 10^{-5}$ metres
$\gamma_s = 2200$ kilograms (weight)/cu.metre
$v_o = 0.45$ metres/second

The transporting gas is air.

For the values of factors a and b of Equations (29) and (37) the experimental values

$a = 8 \cdot 10^{-3}$
$b = 1$

were found in tests carried out in a conduit of the diameter D = 36 millimetres in dilute-stream ($\varepsilon_s < 0.005$) transportation.

The value of the friction coefficient, as referred to the empty tube, is $\lambda = 0.03$. By using data published by WEBER [9], the connection between the concentration of the solid and factor a can be described by the following empirical formula:

$$a = 8 \cdot 10^{-3}\, e^{-0.0585\,\varepsilon_s} \tag{38}$$

The particle flow rate values, as calculated by Equation (37), are illustrated as a function of gas rate in Fig.1. Measured data pertaining to transportation in a dilute stream (ε_s < 0.005) are also included in the Figure. The pressure-drop relations, in accordance with Equation (29) for the case of transportation of sodium bicarbonate are shown in Fig.2.

By substituting the pressure drop and particle flow rate values, as expressed by Equations (29) and (37), into the objective function (8), the specific expenditure of transportation as the function of gas flow rate and solid concentration can be determined. The results of these calculations are illus-

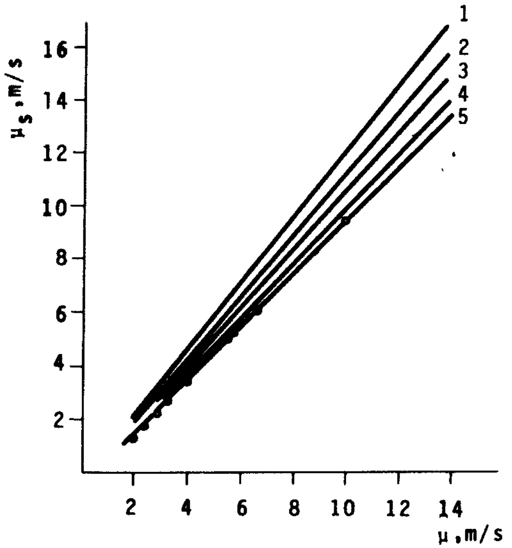

Fig.1. 1 - ε_s = 0.20; 2 - ε_s = 0.15; 3 - ε_s = 0.10; 4 - ε_s = 0.05; 5 - ε_s = 0.01

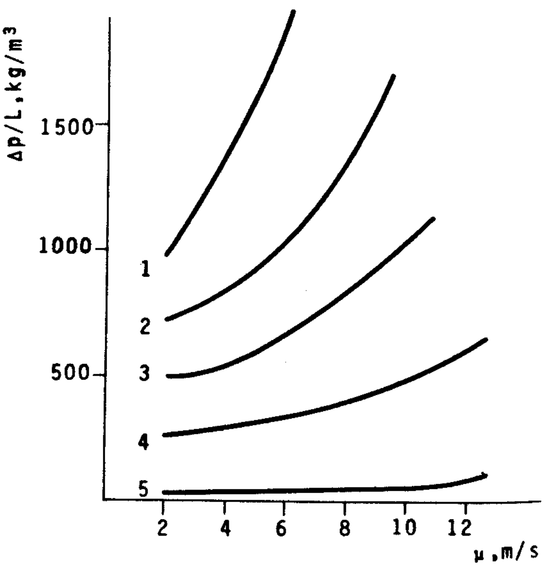

Fig.2. 1 - ε_s = 0.46; 2 - ε_s = 0.31; 3 - ε_s = 0.21; 4 - ε_s = 0.11; 5 - ε_s = 0.01

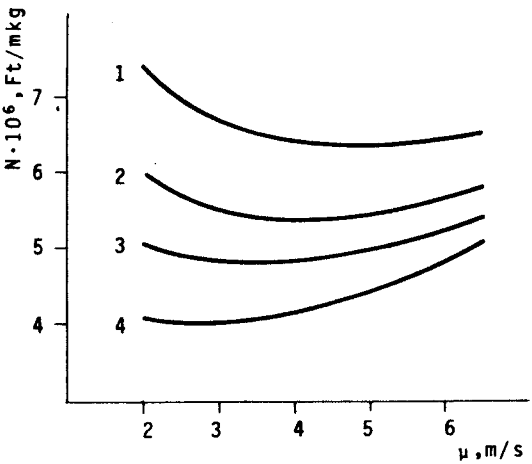

Fig.3. 1 - ε_s = 0.11; 2 - $_s$ = 0.21; 3 - ε_s = 0.31; 4 - $_s$ = 0.46

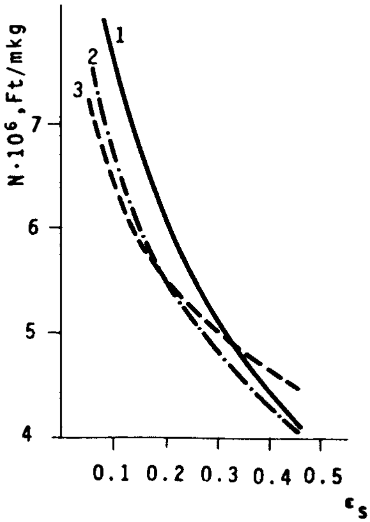

Fig.4. 1 - μ = 2.0 m/sec; 2 - μ = 3.5 m/sec; 3 - μ = 5.0 m/sec

trated in Fig.3 and 4 for an output of 1000 kilograms(weight)/hour if the values of the constants contained in the aim function are the following:

C_a = 30 Forints/kilogram (weight)

γ_a = 7,900 kilograms (weight)/cu.metre

δ_a = 0.01 metre

τ_a = 72,000 hours

C_e = $3 \cdot 10^{-6}$ Forint/metre kilogram (weight)

It is clearly apparent from the Figures that the specific expenditure of transportation shows a monotonous decrease with increasing solid concentration. From an economical point of view it is preferable to choose the parameters of transportation so as to have as high a solid concentration in the transporting conduit as possible.

The transportation expenditure, when examined as a function of the gas flow rate, exceeds a minimum. The flow rate value corresponding to this minimum decreases with increasing solid concentration. The optimum value can be determined by means of Equation (21). The value of the right-hand side of the Equation (NU in the following) as a function of gas flow rate and at various concentrations is shown in Fig.5. The value of the ratio at the left-hand side of Equation (21) is

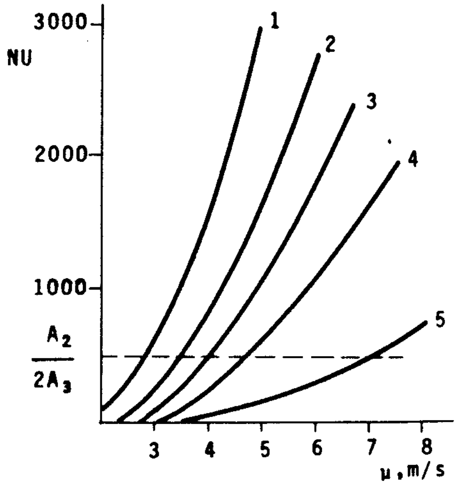

Fig.5. 1 - ε_s = 0.46; 2 - ε_s = 0.31; 3 - ε_s = P.21; 4 - ε_s = 0.11; 5 - ε_s = 0.01

$$\frac{A_2}{2\ A_3} = 484$$

at the values of the economical coefficients given in the foregoing and at an output of 1000 kilograms (weight)/hour. The intersection point of this straight line with the curves of various ε_s parameter values directly gives the optimum gas flow rate pertaining to the actual solid concentration. The relation between the optimum rate and concentration is illustred in Fig.6.If the highest material

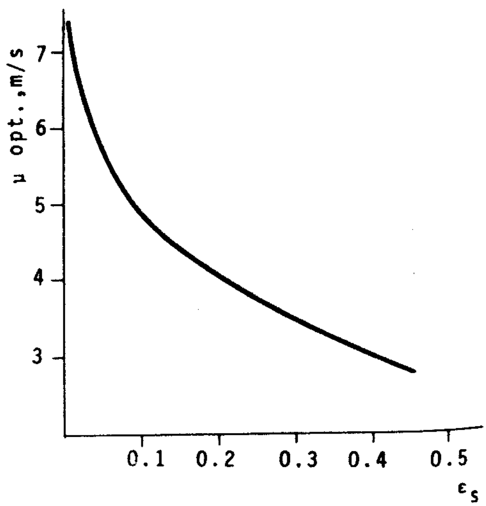

Fig.6.

concentration is substituted into the value of φ, the gas flow rate determined on the basis of Equation (21) gives the lowest possible expense of transportation.

If the optimum values of the operational parameters are known, it is also possible to determine the optimum values of the variables of the original objective function (5). The solid flow rate pertaining to the $U_{optimum}$ and the chosen ε_s values can be calculated from Equation (37), and the diameter of the transport conduit from Equation (6). The amount of gas necessary for the transportation may be determined by Equation (7).

The calculations carried out so far covered the whole range of theoretically possible solid concentrations, from $\varepsilon_s = 0$ to $\varepsilon_s = 1 - \varepsilon_m$. Decisions concerning the practical upper limit of increasing the solid concentration - either by modification of the transport conduit [7] or by application of an auxiliary procedure, without modifying the aim function - require further investigation.

SYMBOLS USED

A - cross section of conduit (sq. metre)

A_h - area of the projection of the particle accumulation in a direction perpendicular to the direction of flow (sq. metre)

C_1 - constant

C_a - cost of the material of the conduit [Forints/kilogram (weight)]

C_e - cost of energy [Forints/metre kilogram (weight)]

C_h - resistance coefficient of the particle accumulation

D - internal diameter of the conduit (metre)

D_k - external diameter of the conduit (metre)

d_o - diameter of the particle (metre)

G_g - weight flow rate of the transporting gas [kilogram (weight)/second]

G_s - weight flow rate of the solid (kilogram (weight)/second)

k_{1v} - collision coefficient measured in a horizontal conduit (metre)$^{-1}$

k_2 - proportionality faotor

K - motion-inhibiting force [kilogram (weight)]

L - length of conduit (metre)

N - specific cost of transportation [Forints/metre kilogram (weight)]

N_a - amortization expense ratio [Forints/metre kilogram (weight)]

N_e - energy expense ratio [Forints/metre kilogram (weight)]

p - pressure [kilogram (weight)/sq.metre]

Δp - pressure drop [kilogram (weight)/sq.metre]

S_g - friction forces in the gas [kilogram (weight)]

T_g - inertia force of the gas [kilogram (weight)]

T_s - inertia force of the solid [kilogram (weight)]

u - gas flow rate referred to the total conduit cross section (metres/second)

u_g - actual flow rate of the gas (metres/second)

u_s - flow rate of the solid particles (metres/second)

v - relative rate between gas and solid (metres/second)

v_o - terminal free-falling velocity of single particle (metres/second)

v_s - terminal free-falling velocity of particle in a suspension of porosity ε, (metres/second)

α - slope of the conduit, as compared to the horizontal

γ_a - specific gravity of the conduit material [kilogram (weight)/cu.metre]

γ_g - specific gravity of the gas [kilogram (weight)/cu.metre]

γ_s - specific gravity of the solid [kilogram (weight)/cu.metre]

δ_a - wall thickness of the conduit (metre)

ε - volume ratio of gas

ε_s - volume ratio of solid

ε_m - minimum gas volume ratio

λ - conduit friction coefficient

λ_j - additional conduit friction coefficient

ξ_s - friction coefficient

τ_a - amortization time (sec)

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РЕЗЮМЕ

Удельная затрата энергии транспортировки твердых зернистых материалов при помощи газового потока, и таким путем денежные расходы транспорта в значительной мере зависят от расчета транспортного провода и показателей эксплуатации. При проектировке транспортной системы - в случае определенной мощности транспорта - диаметр провода и количество транспортирующего газа необходимо выбрать с таким расчетом, чтобы расходы транспортировки были минимальными. Задача решена авторами введением вспомогательных переменных. Для определения оптимальных величин показателей процесса - скорость газа, объемная доля твердого вещества - описан метод вычисления. Применение метода представлено на примере вертикального транспорта кислого карбоната натрия.