AIR LIFT I. DETERMINATION OF IN THE AIR LIFT TANK MOVING SOLID PARTICLE PARAMETERS

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Abstract
One of the most important vertical pneumatic conveying equipment is the air lift. The paper deals with the mathematical-physical model for describing the important physical parameters of the air lift. By applying the continuity and the momentum equations written on the control volume we have got differential equations. The equations has been solved using Runge – Kutta method. Diagrams - pressure, solid and air velocity, and concentration – obtained as a result of solutions gives a presentation on the basis of a given example.

Nomenclature

A_o [m^2]	particle cross section
a_n [m/Pa]	constant
b [m]	height of beginning of the pipe over distribution layer
b_n [m/Pa]	constant
C_D [-]	drag coefficient
d [m]	diameter
d_o [m]	diameter of solid particle
F [N]	drag force
F_f [N]	friction force
f [-]	friction factor
G_1 [N]	weight of a particle
g [m/s^2]	acceleration of gravity
H [m]	height of the fluidized column in the air lift tank
k_o [m/s]	constant characteristic of the distribution layer
m_1 [kg]	mass of one particle
$\dot{m}_g$ [kg/s]	mass flow of the gas flowing towards the nozzle over the distribution layer
$\dot{m}_{g1}$ [kg/s]	mass flow of the conveying gas coming through the distribution layer
$\dot{m}_{gk}$ [kg/s]	mass flow of the conveying gas flowing out of the nozzle
$\dot{m}_{g2} - \beta \dot{m}_{g1}$	mass flow of the gas flowing across the tank
p [Pa]	pressure
p_o [Pa]	atmospheric pressure
p_1 [Pa]	pressure under the distribution layer
p_k [Pa]	pressure of the gas at outlet of the nozzle
p_t [Pa]	pressure of the fluidized tank over distribution layer in place $R = R_t$
p_j [Pa]	pressure under the nozzle
R [m]	radius
R [J/kgK]	gas constant
Re [-]	Reynolds number
R_p [m]	radius of the conveying pipe
R_t [m]	radius of the air lift tank
v [m/s]	velocity
v_{g1} [m/s]	velocity of the gas coming across the distribution layer at R=R1
v_j [m/s]	velocity under the nozzle
v_k [m/s]	velocity at the outlet of nozzle
v_m [m/s]	material velocity in the streaming layer
$v_{mo}=\varphi\, v_m$ [m/s]	sedimentation velocity in the tank

Greek letters

α [degree]	angle
$\beta = \dfrac{\dot{m}_{g2}}{\dot{m}_{g1}}$ [-]	relative number
$\varphi = \dfrac{v_{mo}}{v_m}$	relative number
μ [kg/ms]	absolute viscosity of the air
κ [-]	ratio of specific heats
ρ_b [kg/m^3]	bulk density in the fluidized tank
ρ_g [kg/m^3]	gas density
ρ_{go} [kg/m^3]	gas density at

	atmospheric pressure
ρ_m [kg/m^3]	material concentration
ρ_s [kg/m^3]	solid density
Indices	
f	friction
g	gas
m	material
j, k, p, t, 1	mark of place
1	one particle

Introduction

Air lift is used widely for the vertical conveying of various granular and powdery materials. This conveying equipment is suitable for transporting high (10–200 t/h) mass flows to high (max. 70-80 m) vertical distances.

The conveying equipment enables the continuous, automatic, dust-free (environmental-friend) transportation. The operation of the equipment is reliable, it adapts automatically to variations in delivery capacity and enables virtually erosion-free transport. It is widely used for the transport of cement, alumina, fly ash, limestone powder, etc.

1. Two-phase flow in air lifts

The operating air enters in the air lift at the place marked 1 according to the sketch shown in Figure 1 and flows to the nozzle marked 2. High velocity air stream exiting from the nozzle entrains the powdery material brought into fluidized state by the air flow passing through the air distribution layer marked 4 and flowing towards the nozzle.

The primary air jet and the fine-grained solid material mixed in it, and flows upwards with a reduced velocity in the initial section (starting section) of the vertical conveying pipe marked 5.

Two partial processes, determining fundamentally the operation of the air lift. These are:

2.1. Radial flow of solid material-air mixture towards the nozzle above the air distribution layer

2.2. Mixing of air-solid material stream with air leaving the nozzle in the starting section (in the initial section of the vertical conveying pipe)

(This section is discussed in the paper [3])

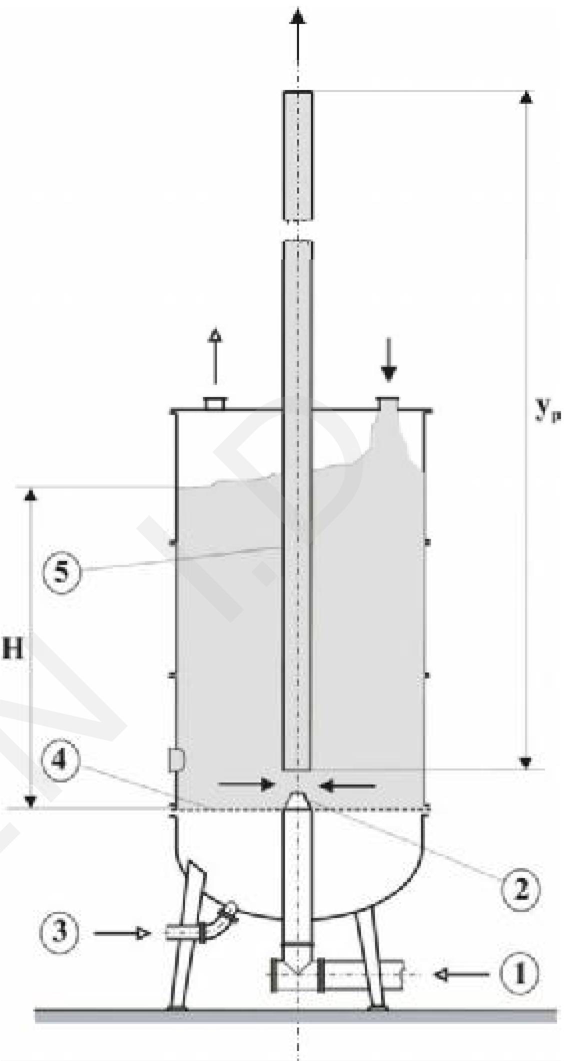

Fig. 1 Sketch of air lift

2.1.1. Radial flow of air towards the nozzle above the air distribution layer

Pressure „p_1" under the air distribution layer can be considered to be constant. The pressure level at place „R_t" above the air distribution layer decreases from value „p_t" determined by the material column of height „*H*" to value „p_k" assumed at place „R_p" (Figure 2) due to the dynamic pressure of air flowing out of the nozzle. The value of overpressure „p_t" depends on the layer height of the fluidized column in the tank.

This allows the following equation to be set up:

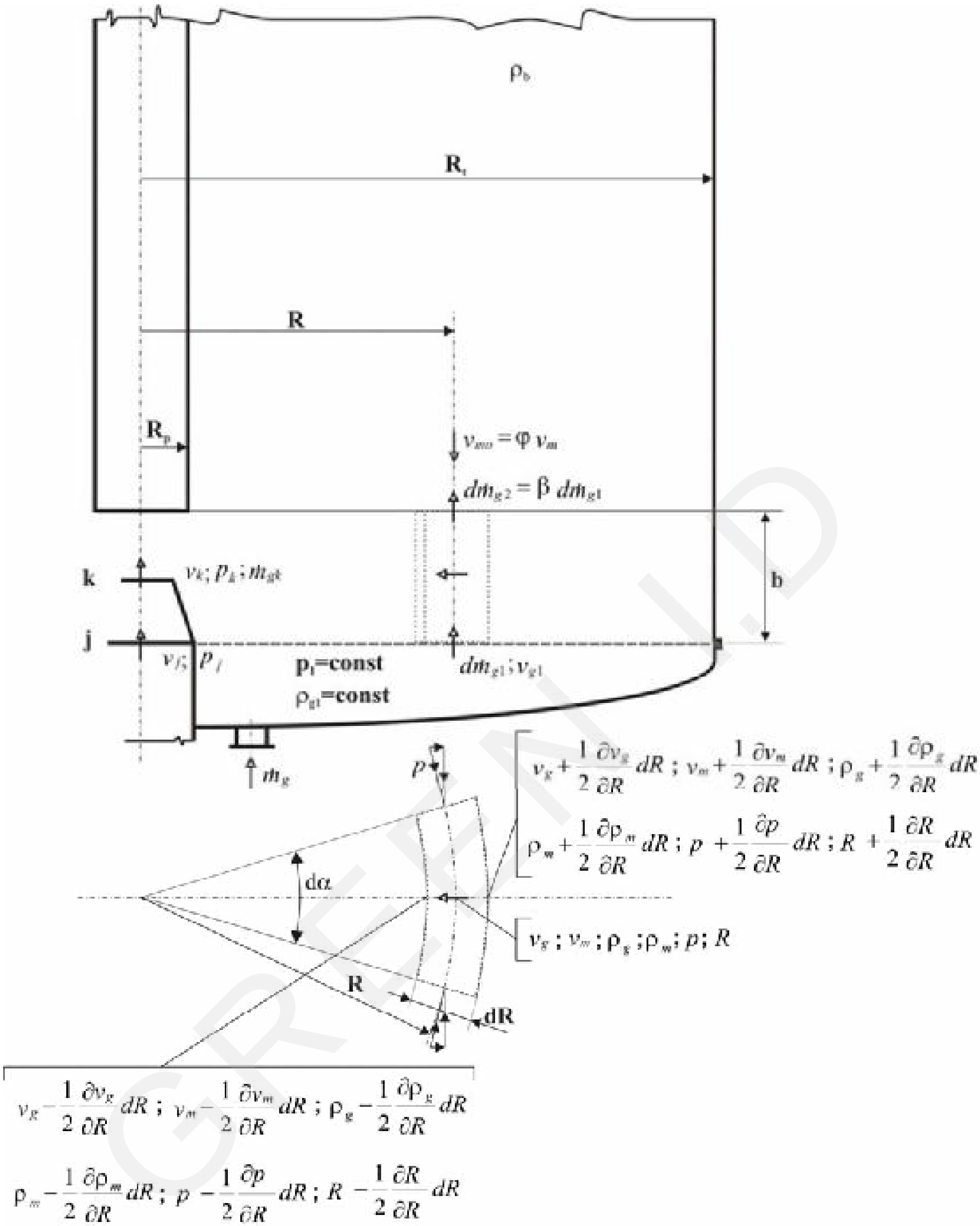

Fig. 2 Control volume in the radial flow on distribution layer

$$p_t - \rho_m g H \qquad (1)$$

The air flowing out of the nozzle is considered to be frictionless, and the change in state adiabatic. The velocity of the gas leaving the nozzle is:

$$v_k = \left[2\frac{\kappa}{\kappa-1} R T_j \left(1-\left(\frac{p_k}{p_j}\right)^{\frac{\kappa-1}{\kappa}}\right)+v_j^2\right]^{1/2} \qquad (2)$$

Using velocity „v_k” taken from equation 2 and the known velocity „v_j” gives the following equation for pressure ratio „p_k/p_j”:

$$\frac{p_k}{p_j} = \left[1-\frac{\kappa-1}{\kappa}\frac{v_k^2-v_j^2}{2RT_j}\right]^{\frac{\kappa}{\kappa-1}} \qquad (3)$$

Thus, pressure „p_k” can be determined of the value of „p_j”.

Assuming the variation in pressure levels to be parabolic, pressure distribution over the distribution layer can be described by the following equation:

$$p = \frac{1}{2a_n}\left(-b_n + \sqrt{b_n^2 + 4a_n R}\right) \qquad (4)$$

The constants of this equation can be calculated from pressure values „p_t" and „p_k". These can be described as:

$$a_n = \frac{1}{p_k\, p_t}\,\frac{R_p\, p_k - R_t\, p_t}{p_t - p_k} \qquad (5)$$

$$b_n = \frac{R_t - a_n\, p_k^2}{p_k} \qquad (6)$$

Portion $d\dot{m}_{g2} = \beta\, d\dot{m}_{g1}$ of mass air flow „$d\dot{m}_{g1}$" entering through an annulus surface element of the air distribution layer performs the fluidization of the column of „H" height in the tank and exits from the tank, while the balance marked „$d\dot{m}_g$" entrains the particles as it flows towards the nozzle (the lower pressure place).

The mass flow of air flowing towards the nozzle is:

$$d\dot{m}_g - (1-\beta)\, d\dot{m}_{g1} -$$

$$= (1-\beta)\frac{p_1 - p}{k_o\,\rho_{g1}}\,\rho_{g1}\, R dR 2\pi =$$

$$= (1-\beta)\frac{2\pi}{k_o}\left[p_1 + \frac{b_n}{2a_n} - \frac{1}{2a_n}\left(b_n^2 + 4a_n R\right)^{1/2}\right] R dR \qquad (7)$$

The integration of this equation gives the following expression for the mass flow of air flowing towards the nozzle:

$$\dot{m}_g = (1-\beta)\frac{2\pi}{k_o}\left\{\left(p_t + \frac{b_n}{2a_n}\right)\frac{R_t - R}{2} -\right.$$

$$-\frac{2}{480\,a_n^3}\left[\left(12a_n R_t - 2b_n^2\right)\left(4a_n R_t + b_n^2\right)^{3/2} -\right.$$

$$\left.\left. -\left(12\,a_n R - 2b_n^2\right)\left(4\,a_n R + b_n^2\right)^{3/2}\right]\right\} \qquad (8)$$

The calculation of the parameters of the solid material-air mixture flowing towards the nozzle will require the value of derivative „dv_g/dR" of the air velocity. Let us set up the equation of continuity for this gas for the control volume marked in Figure 2 with the following assumptions taken into consideration:

- The tightening effect caused by the particles in the control volume will not be taken into account
- The change in the state of the gas is considered to be isometric.

$$R\, d\alpha\, dR\, \rho_{g1}\frac{p_1 - p}{k_o\,\rho_{g1}} +$$

$$+\left(R + \frac{dR}{2}\right)\left(\rho_g + \frac{d\rho_g}{2}\right)\left(v_g + \frac{dv_g}{2}\right) d\alpha\, b -$$

$$-\left(R - \frac{dR}{2}\right)\left(\rho_g - \frac{d\rho_g}{2}\right)\left(v_g - \frac{dv_g}{2}\right) d\alpha\, b -$$

$$-\beta\, R\, d\alpha\, dR\, \rho_{g1}\frac{p_1 - p}{k_o\,\rho_{g1}} = 0 \qquad (9)$$

After transformation and rearranging, as well as neglecting second-order members, the continuity equation can be written in the following form:

$$\frac{dv_g}{dR} = -(1-\beta)\frac{(p_1 - p)\,p_o}{b\,k_o\,\rho_{go}\,p} - \frac{v_g}{R} - \frac{v_g}{p}\frac{dp}{dR} \qquad (10)$$

(The gas mass flow calculated from the value obtained after the integration of equation 10 is identical with the value calculated with relationship 8.)

Figure 3 shows the radial distribution of gas mass flow $\dot{m}_g(R)$ calculated with relationship 8, using the data of an example described later.

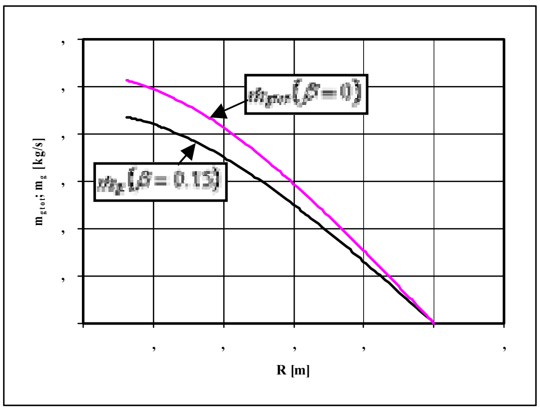

Fig 3 Gas mass flow distribution

2.1.2. Solid material flow towards the nozzle. Continuity equation written for particles

Using the symbols of Figure 2, the continuity equation for the particles in the control volume can be written in the following form:

$$R\,d\alpha\,dR\,\rho_b\varphi\,v_m + \left(R+\frac{dR}{2}\right)d\alpha\,b\left(\rho_m+\frac{d\rho_m}{2}\right)\left(v_m+\frac{dv_m}{2}\right) - \left(R-\frac{dR}{2}\right)d\alpha\,b\left(\rho_m-\frac{d\rho_m}{2}\right)\left(v_m-\frac{dv_m}{2}\right) = 0 \quad (11)$$

After transformation and rearranging, as well as neglecting second-order members, we obtain the following equation:

$$\frac{d\rho_m}{dR} = -\frac{\rho_b\varphi\,v_m}{b\,v_m} - \frac{\rho_m}{R} - \frac{\rho_m}{v_m}\frac{dv_m}{dR} \quad (12)$$

2.1.3. Momentum equation written for particles

The momentum equation can be written in the following form:

$$\left[\left(R+\frac{dR}{2}\right)\left(\rho_m+\frac{d\rho_m}{2}\right)\left(v_m+\frac{dv_m}{2}\right)^2 - \left(R-\frac{dR}{2}\right)\left(\rho_m-\frac{d\rho_m}{2}\right)\left(v_m-\frac{dv_m}{2}\right)^2\right]b\,d\alpha = -dF + dF_f \quad (13)$$

„dF" on the right side of equation 13 means the drag force on the particles, while „dF_f" means the friction force.

These can be written in the following form:

$$dF = \frac{\rho_m}{m_1}b\,R\,d\alpha\,dR\,\frac{\rho_g}{2}A_o C_D\left(|v_g|-|v_m|\right)^2 \quad (14)$$

According to Kaskas [1], drag coefficient „C_D" can be written in the following form:

$$C_D = \frac{24}{\mathrm{Re}} + \frac{4}{\sqrt{\mathrm{Re}}} + 0.4$$

$$\mathrm{Re} = \frac{(v_g - v_m)\,d_s\,\rho_g}{\mu_g} \quad (15)$$

The Coulomb friction force is:

$$dF_f = f\,\rho_m\,g\,R\,d\alpha\,b\,dR \quad (16)$$

After transformation and rearranging, as well as neglecting second-order members and taking equation 12 into consideration, we obtain the following relationship:

$$\frac{dv_m}{dR} = \frac{\rho_b\varphi\,v_m}{b\,\rho_m} - \frac{\rho_{go}\,p\,A_o C_D}{2m_1 v_m\,p_o}\left(|v_g|-|v_m|\right)^2 + \frac{f\,g}{v_m} \quad (17)$$

The parameters of solid material-air mixture flowing towards the nozzle can be calculated with the use of equations 4, 10, 12, 17 and 19.

The calculations have shown that a dead zone is developed on the fluidization layer. This means that material flow towards the flow in the layer of „b" height does not start from the inside wall of the tank marked „R_t", but only from the radius $R_i < R_t$. Therefore the value of radius „R_i" has to be high enough to satisfy condition $F \geq F_f$ for drag force „F" calculated with the radial air velocity determinable from gas mass flow „$\dot{m}_g$" passing through surface section $\Delta A = \pi\,(R_t^2 - R_i^2)$ of the distribution layer.

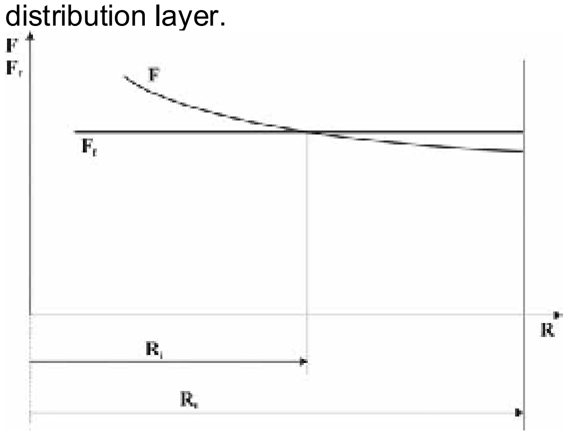

Fig. 4 Figure for determining "R_i" value

Thus, in order to start numerical calculations, the value of „R_i" has to be determined as the first step (see Figure 4).

Using equation 8, mass flow „$\dot{m}_g$" is calculated at various „R" values.

The velocity of gas flowing towards the nozzle, at various values of „R" and with equation 4 taken into consideration, is obtained as:

$$v_g = \frac{\dot{m}_g}{2R\pi\, b\, \rho_g} = \frac{\dot{m}_g\, p_o}{2R\pi\, b\, \rho_{go}\, p} =$$

$$= \frac{\dot{m}_g\, p_o 2\, a_n}{2R\pi\, b\, \rho_{go}\left(-b_n + \sqrt{b_n^2 + 4\, a_n R}\right)} \qquad (18)$$

Drag force „*F*" is calculated by equation 14 with gas velocity „v_g" at particle velocity v_m=0. Repeating this at several assumed radii allows curve *F(R)* to be plotted. The Coulomb friction force "F_f" can be calculated by equation 16. The point of intersection of the two curves gives the „R_i" value (see Figure 4).

2.1.4. Diagrams obtained by solving the equations

Equations 4, 10, 12 and 17 have been solved using the numerical method of Runge-Kutta. The data of the example used are:
b=0.2 m; H=5 m; k_o=50000 m/s; $\dot{m}_m$=30 kg/s; $\dot{m}_g$=0.435 kg/s; p_1=145.3 kPa; p_t=139.23 kPa; p_k=133.23 kPa; R_t=1 m; R_p=0.125 m; v_k=100 m/s; β=0.15; ρ_b=800 kg/m^3; ρ_s=2600 kg/m^3; d_o≈1.5*10^{-4} m; solid material: fly ash; R_i=0.8074 m.

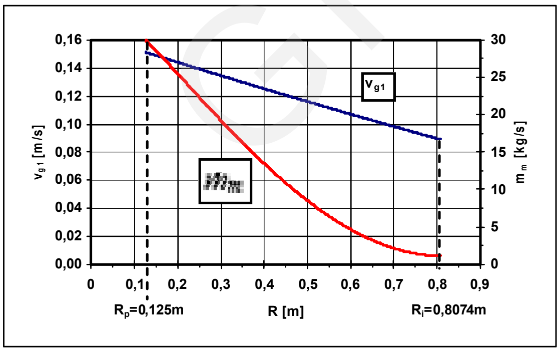

Fig. 5 Loosening velocity and solid material mass flow distribution

In Figure 5 the velocity distribution of air flowing through the distribution layer (layer 2 in Figure 1) and the mass flow variation flowing towards the nozzle are plotted as a function of radius.

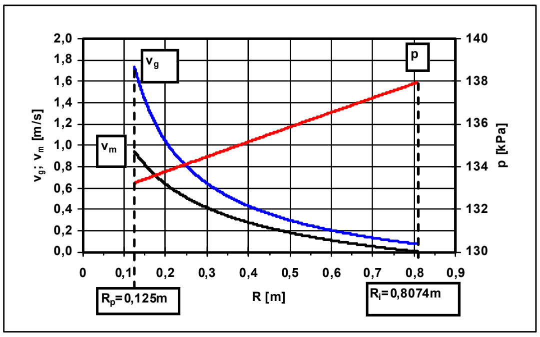

Fig 6 Gas-, solid material velocity and pressure distribution

Figure 6 shows the distributions of velocities in the gas flowing towards the nozzle, particle velocities and pressures over the distribution layer within the layer of „*b*" height (see Figure 2).

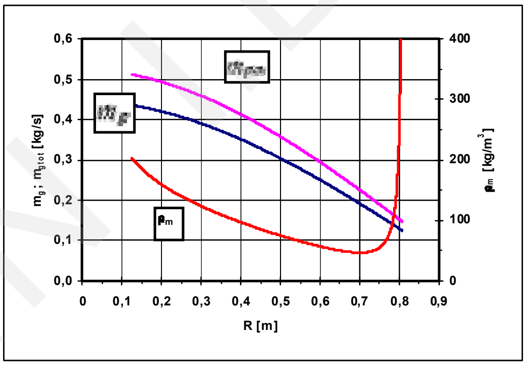

Fig. 7 Gas mass flow and material concentration distribution

Figure 7 shows the variations in material concentration „ρ_m" and radial gas mass flow „$\dot{m}_g$".

Conclusions and remarks

The model presented in this paper is suitable for taking the first step for the description of the complex flow taking place in air lifts. The equations derived, allows the main parameters to be calculated and the main dimensions of the equipment to be determined.

The following experiments need to be made in order to improve and verify the model used for the description of the two-phase flow taking place in air lift tanks.

- Determine relative number marked „φ" for velocity v_{mo} = φ v_m of material arriving from above into the control volume assumed in Section 2.1.

- The portion marked „β" of the air volume passing through the distribution layer provides the fluidization of the material column of „H" height. The value of „β" has to be determined by experiments.
- The pressure variation over the distribution layer was assumed to be parabolic in this paper. The value of this assumption has to be verified by experiments.
- The radius marked „R_i" of the dead zone discussed in Sub-section 2.1.2 has to be verified by experiments.

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