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DEVELOPMENT OF METHODS FOR REDUCING THE VOLUME OF ASPIRATION DURING OVERLOADS OF GRANULAR MATERIALS BY BUCKET ELEVATORS

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Abstract. The schemes of aspiration of elevator overloads have been developing. Balance equations of ventilation of aspiration covers are compiled. The system of equations for determination of the volumes of ventilating air for a standard node overload are formulated and solved. Ways of reducing productivity of aspiration systems are offered and analytically substantiated.

1 INTRODUCTION

Aspiration is one of the most effective methods that have been used to control dust in conveying free-fl owing materials [1-2]. As the power of technological equipment increases, there is an increase in the power intensity of aspiration systems and in the loss of the free-flowing material in extracting dusted air from aspiration shelters. The requirement arises to attain the highest sanitary-hygienic effect with less expenditures. The most common methods for decreasing energy consumption by aspiration is decreasing the volumes of air penetrating through leaks and the volumes of air ejected by the stream of the free-fl owing material [3- 4] by organizing ejected air circulation in the charging chute.

The purpose of this article is developing the methods of reducing the induced air volume and analyzing the numerical calculations of transloading nodes of loose materials in bucket elevators.

Aspiration volumes in the classical aspiration layout for elevator handling of grain are determined by balance equations. Basic components of both equations comprise volumetric flow rates of air entrained into aspirated cowls through leaking joints and process openings by the negative pressure (maintained inside cowls by an aspiration unit) and flow rates of air transferred in ducts.

Flow rates of transferred air may be determined using algorithms devised by solving combined non-linear equations with a joint use of iteration and bisection methods.

Regularities of air cross-flow and circulation patterns in conveyor-to-conveyor grain handling with a bypass duct connecting the inner chamber of a double-walled cowl with the cowl of the driving drum can be studied using equations for pressure losses in ducts and air flow rate balance equations for cowls and junction points. Analysis of these regularities has shown that efficient operation of the bypass duct requires negative pressure inside the cowl of the upper unaspirated conveyor to exceed the negative pressure in the buffer (inner) chamber.

The numbering of formulas and drawings begins in the article «Features of the settlement scheme aspiration of elevator overloads» of these proceedings.

2 ASPIRATION VOLUMES

Flows rate of air evacuated from cowls by local suction units of the aspiration system are determined using the air balance equation. So, for aspirated cowls for elevator handing of grain, the following equations result:

For the cowl of the elevator "boot", due to (20):

$$Q_e = Q_0 + Q_2 + Q_\text{b} - Q_1 = Q_0 + \Delta Q + Q_\text{b} . \tag{73}$$

For the cowl of the location of grain loading from the elevator onto the upper conveyor, due to (22):

$$Q_a = Q_3 + Q_\text{c} . \tag{74}$$

Flow rates of air entering the cowl through leaky locations are determined using the value of negative pressure maintained by a local suction unit, and the total leakage area.

For the cowl of the elevator "boot", the recommended target negative pressure is $h_\text{b} = 10 \div 30$ Pa, then, due to (18), (30) and (33), the flow rate of air arriving through leakage areas would be:

$$Q_\text{b} = \sqrt{h_\text{b}/R_\text{b}} = 0.913 F_\text{b} \sqrt{h_\text{b}/\rho} . \tag{75}$$

Negative pressure for the upper cowl is determined by the structural design of the cowl. For a grain measuring $d_e > 3$ mm, it equals to $h_\text{b} = 6$ for a double-walled cowl or $h_\text{b} = 11$ for a single-walled cowl.

The flow rate of air entering the cowl through leakage areas is equal, in view of (16), (32) and (33), to:

$$Q_\text{c} = \sqrt{h_\text{c}/R_\text{c}} = 0.913 F_\text{c} \sqrt{h_\text{c}/\rho} . \tag{76}$$

The flow rate of air passing through the loading chute is determined by equation (56). If both sides of this equation are divided by L_{k0}, the following dimensionless equation for cross-flow of air on will result:

$$\varphi_0^2 = \frac{\text{Bu}}{3}\left[\left|1-\varphi_0\right|^3 - \left|n-\varphi_0\right|^3\right] + \text{Eu}_0 , \tag{77}$$

where

$$\varphi_0 = \frac{Q_0}{L_{k0}} = \frac{u_0}{v_{k0}} ;\ n = \frac{v_{n0}}{v_{k0}} ; \tag{78}$$

u_0 is the velocity of air in loading chute (m/s); u_{n0}, u_{k0} are the velocities of a grain stream at inlet/outlet of the loading chute (m/s); Bu is the Butakov-Neykov number [3] that in this case is equal to:

$$\mathrm{Bu}_0 = 3\cdot E_0 \frac{L_{k0}}{R_\mathrm{d} + R_0} = K_0 \psi_{y0} \frac{1.5}{d_e} \cdot \frac{G_\mathrm{m} v_{k0}}{\rho_\mathrm{m} S_0 a_{t0} \sum \zeta_0}; \quad (79)$$

$$\sum \zeta_0 = \zeta_0 + \zeta_n \left(\frac{S_0}{F_\mathrm{d}} \right)^2; \quad (80)$$

Eu_0 is the Euler's number, in this case equal to:

$$\mathrm{Eu}_0 = \frac{h_\mathrm{b}}{(R_\mathrm{d} + R_0) L_{k0}^2} = \frac{2h_\mathrm{b}}{\sum \zeta_0 v_{k0}^2 \rho}. \quad (81)$$

A similar criterial equation can be proposed as well for the discharge chute:

$$\varphi_\mathrm{g}^2 = \frac{\mathrm{Bu}_\mathrm{g}}{3} \left[\left| 1 - \varphi_\mathrm{g} \right|^3 - \left| n - \varphi_\mathrm{g} \right|^3 \right] + \mathrm{Eu}_\mathrm{g} - \frac{h_\mathrm{s}}{0.5 \zeta_\mathrm{g} v_{kg}^2 \rho}; \quad (82)$$

$$\mathrm{Bu}_\mathrm{g} = K_0 \psi_{yg} \frac{1.5}{d_e} \cdot \frac{G_\mathrm{m} v_{kg}}{\rho_\mathrm{m} S_\mathrm{g} a_{tg} \zeta_\mathrm{g}}; \quad (83)$$

$$\mathrm{Eu}_\mathrm{g} = \frac{h_\mathrm{c}}{0.5 \zeta_\mathrm{g} v_{kg}^2 \rho}. \quad (84)$$

However, it would be impossible to determine the respective flow rate as negative pressure inside the unaspirated cowl of the elevator “head” is unknown.

Therefore air cross-flow rates will be determined iteratively using the procedure (67). The algorithm for the aspiration volume computation program includes determining Q_0 and Q_g using the bisection method and computing flow rates Q_1 and Q_2 using formulas (69) and (70).

As an example, consider elevator handling of wheat with the following parameters for the loading chute: $E_0 = 4$; $L_{k0} = 1.6$; $L_{n0} = 1$; h_b – var ($h_\mathrm{b} = 16.8$ for charts plotted on Fig. 6); $R_0 = 50$; for enclosures of the carrying and return runs of elevator conveyor: $E_1 = 200$; $R_1 = 21$; $L_1 = L_2 = 1$; $E_2 = 400$; h_s – var; $R_2 = 22$; for the discharge chute: $E_\mathrm{g} = 5$; $L_{kg} = 2$; $L_{ng} = 0.5$; R_s – var ($R_\mathrm{s} = 40$ for charts plotted on Fig.5); $R_3 = 10$; $h_k = 10$.

Findings from computations of air cross-flow rates are summarized on Fig.5 and 6. As this data indicates, increasing negative pressures inside the aspirated cowl of elevator boot (Fig. 5) lead to increased flow rates of ejected air in the loading chute Q_0 and a greater flow rate of air in the return run enclosure of the conveyor. At the same time, negative pressure within elevator head cowl h_s increases. Only the flow rates of air in discharge chute Q_3 and the enclosure of conveyor carrying run Q_1 decrease. This happens because increasing negative pressure h_b reduces the ejecting capacity of the grain stream inside the discharge chute (as a direct consequences of increasing h_s) and of laden buckets inside the carrying run enclosure of the bucket elevator.

The value of h_s increases especially strongly with tighter sealing of the elevator head cowl (Fig.6). This reduces the flow rates Q_3, Q_2 and increases the flow rate of ejected air inside the enclosure of the elevator carrying run Q_1.

As for aspiration volumes (Fig.7) they naturally reflect the regularities of air cross-flow patterns in elevator ducts noted above. Thus, aspiration volumes for the cowl of elevator boot Q_b rise with increasing negative pressure h_b .

This occurs not only due to increasing Q_0 but also as a result of greater ejecting capacity of buckets within the return run enclosure of bucket elevator as well as increased flow rate of air arriving into the cowl in question through leakage areas as negative pressure h_b increases (Fig.7a). With increasing negative pressure h_s as a result of decreasing leakage area of the elevator cowl (at higher R_s), aspiration volumes Q_b and Q_a decline somewhat (Fig.7 b). Aspiration volume Q_a decreases as well with increasing negative pressure in the lower cowl h_b .

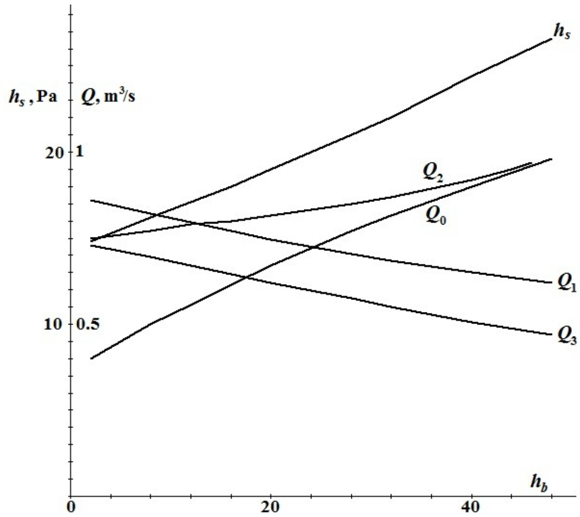

Fig. 5. Variation in air flow rates (Q_0, Q_1, Q_2, Q_3) in ducts and negative pressure (h_s) within the cowl of elevator head as a function of negative pressure in the elevator boot cowl

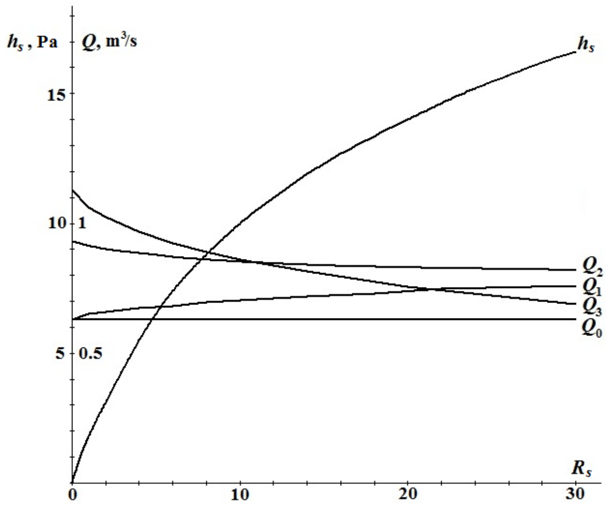

Fig. 6: Variation of air flow rate (Q_0, Q_1, Q_2, Q_3) in ducts and negative pressure in the elevator head enclosure as a function of sealing degree

The total aspiration volume in the first case (with increasing h_b) grows due to increasing volumes of air sucked through leakage areas of elevator boot cowl. If the upper cowl is sealed, the total performance of local suction decreases (Fig. 7 b). Despite that, the required aspiration volume remains high enough even at small negative pressures maintained inside cowls (at $h_b = 16.8$ Pa, $h_c = 10$ Pa and $F_s = 0.1$ m^2 ($R_s = 14.4$ Pa/(m^3/s)^2). The total volume in the example case at hand is 2.06 m^3/s).

3 REDUCING REQUIRED ASPIRATION VOLUMES IN BYPASSED ELEVATOR HANDLING SYSTEMS

The performance of an aspiration system is determined by the total flow rate of air entering through all aspirated cowls as well as unaspirated cowls that are aerodynamically coupled with the former (due to 2.4). Reducing aspiration volumes requires not only sealing the cowl but also decreasing the negative pressures h_b and h_c .

It is well-known that the use of double-walled cowls enables a significant reduction in the optimum negative pressure (at $d_3 \geq 3$ mm the optimum negative pressure inside a single cowl of conveyor loading is $h_c = 11$ Pa, decreasing to $h_c = 6$ Pa in the case of a rigidly-partitioned double-walled cowl.

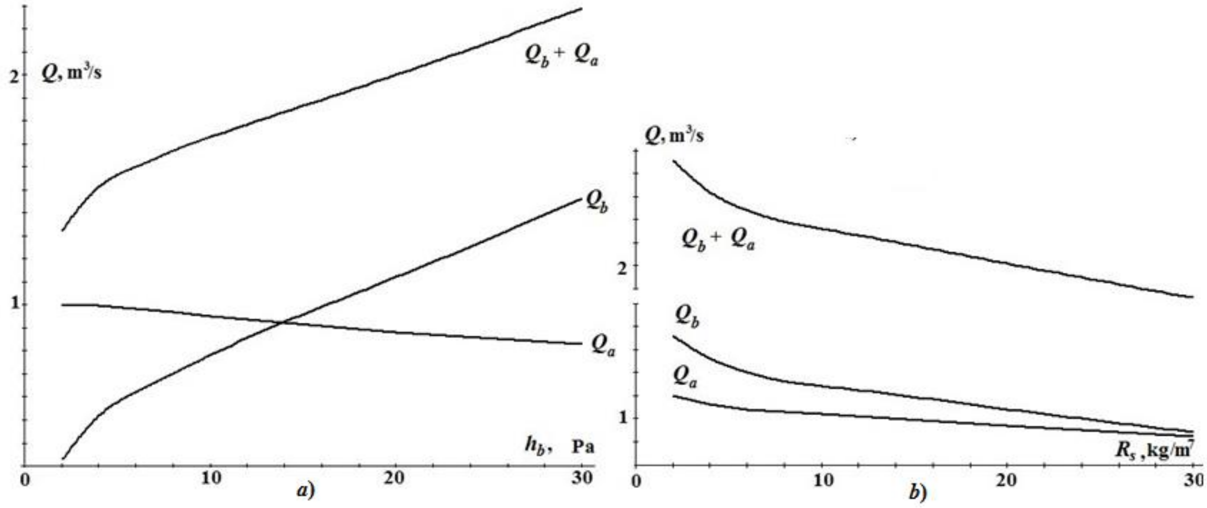

Fig. 7: Variation in aspiration volumes as a function of (a) negative pressure inside the elevator boot cowl at $R_s = 40$, $h_c = 10$ Pa and (b) of the elevator head cowl sealing degree at $h_c = 16.8$ Pa

Unaspirated cowls are purposefully joined by flow-around (bypass) ducts with a positive-pressure zone to inhibit negative pressures. The resulting internal circulation of air would reduce the total volume of air evacuated by suction.

Let's now study the role of these bypass connections by choosing aspiration of elevator loading and unloading units as an example. Let the bottom part of the loading chute be equipped with a special (buffer) chamber that has its internal space connected by flow-around ducts with the cowl of feeder drive drum and the enclosure of elevator head. Grain being handled proceeds from the chamber into the elevator boot enclosure via an orifice of a flapper-type dust trap. In this case aerodynamic drag of the valve produces an excess pressure inside the chamber that forces a part of ejected air to proceed into the flow-around duct and to return into the upper cowls, creating internal circulation flows with flow rates Q_4 and Q_6.

The cowl of elevator head enclosure can be also connected using a bypass duct with the inner chamber of the doubled-walled cowl at upper conveyor loading location (a dust trap in this case is provided by a rigid partition).

Thus, three circulation flows may exist with flow rates of Q_4, Q_6 and Q_7 (see Fig. 6).

We'll begin with considering a classic grain handling facility transferring grain from a belt feeder onto a belt conveyor (Fig. 8).

When a double-walled cowl is used (to contain dust releases when loading grain onto belt conveyor), a bypass duct connects the inner chamber of this cowl with an unaspirated cowl of the feeder driving drum. A positive effect is provided with air flow direction indicated in the chart. In this case:

$$Q_y = Q_c - Q_{bc} = Q_f , \tag{85}$$

i.e. the flow rate of air coming from the inner chamber into unaspirated (outer) chamber Q_y is less than the flow rate of air Q_c flowing over through a chute due to ejection head $P_e\left(Q_c\right)$ and negative pressure in the outer chamber h_y caused by a running fan of the aspiration system.

Let's write down obvious equations of pressure losses in ducts:

$$P_d + P_e\left(Q_c\right) - P_{bc} = R_c Q_c^2 = h_{bc} + P_e\left(Q_c\right) - h_d\,; \tag{86}$$

$$P_{bc} - P_d = P_{bc} Q_{bp}\left|Q_{bp}\right| = h_d - h_{bc}\,; \tag{87}$$

$$P_{bc} - P_y = R_y Q_y^2 = h_y - h_{bc}\,; \tag{88}$$

$$P_a - P_y = R_d Q_d^2 = h_y\,; \tag{89}$$

$$P_a - P_d = R_d Q_d^2 = R_d Q_y^2 = h_d \tag{90}$$

as well as air balance equations:

$$Q_d = Q_c - Q_{bp}\,; \tag{91}$$

$$Q_c = Q_{bp} + Q_y\,; \tag{92}$$

$$Q_a = Q_y + Q_b\,. \tag{93}$$

From (86) it follows that:

$$P_e\left(Q_c\right) - R_c Q_c^2 = h_d - h_{bc}\,. \tag{94}$$

Where it is evident (considering that ejection pressure in the case at hand is greater than pressure losses in the chute) that negative pressure in the feeder cowl must be greater in magnitude than negative pressure in the buffer (inner) chamber:

$$h_d \geq h_{bc}\,. \tag{95}$$

This inequality, the driver of cost savings, can be written in an expanded form accounting for (90) and (88):

$$R_d Q_y^2 \geq h_y - R_y Q_y^2\,. \tag{96}$$

This enables us to determine the minimum flow rate Q_y:

$$Q_y^{\min} = \sqrt{\frac{h_y}{R_d + R_y}}\,. \tag{97}$$

The expanded condition of efficient bypass operation (96) can be presented in another form:

$$R_y \geq \left(\frac{h_y}{h_d} - 1\right) R_d\,, \tag{98}$$

where the role of the buffer chamber is evident. So, absent ($R_y = 0$), the condition (98) will appear as:

$$h_{\text{d}} \geq h_y \, , \tag{99}$$

which would be troublesome to accomplish in actual conditions (considering the difficulties of sealing the feeder cowl). Thus, the buffer chamber increases the likelihood of efficient bypass operation.

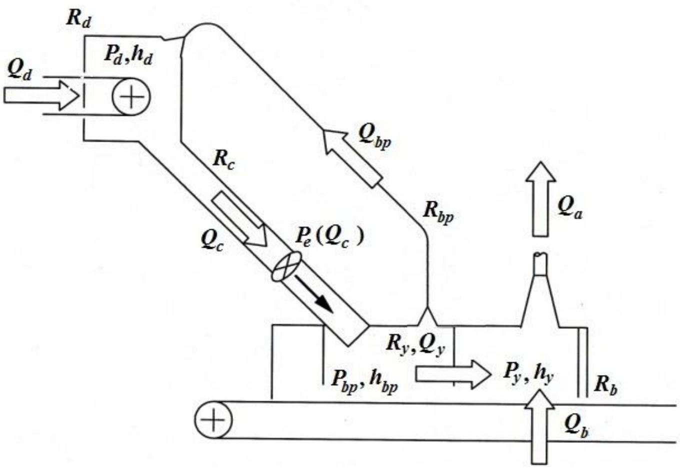

Fig. 8: Aspiration layout of a bypassed handling facility

How precisely is the flow rate Q_y determined by process and structural design parameters of the chute, cowls and the bypass duct?

Let's designate

$$P_{\text{e}}\left(Q_{\text{c}}\right) - R_{\text{c}} Q_{\text{c}} \left|Q_{\text{c}}\right| = L\left(Q_{\text{c}}\right). \tag{100}$$

Then, a jointly solution of equations (86) and (87), gives:

$$Q_{\text{bp}} = \frac{L\left(Q_{\text{c}}\right)}{\sqrt{\left|L\left(Q_{\text{c}}\right)\right| R_{\text{bp}}}} \, , \tag{101}$$

while (87), (88) and (90) combine into:

$$\left(R_{\text{d}} + R_y\right) Q_y^2 = h_y + R_{\text{bp}} Q_{\text{bp}} \left|Q_{\text{bp}}\right| , \tag{102}$$

whence

$$Q_y = \frac{h_y + R_{\text{bp}} Q_{\text{bp}} \left|Q_{\text{bp}}\right|}{\sqrt{\left|h_y + R_{\text{bp}} Q_{\text{bp}} \left|Q_{\text{bp}}\right|\right| \left(R_{\text{d}} + R_y\right)}} \, . \tag{103}$$

Substitution of the resulting expressions for $Q_{\text{f}}\left(Q_{\text{c}}\right)$ and $Q_y\left(Q_{\text{f}}\left(Q_{\text{c}}\right)\right)$ into equation (92) produces the following functional equation for determining Q_{c}:

$$F\left(Q_{\text{c}}\right) = Q_{\text{c}} - Q_{\text{bp}}\left(Q_{\text{c}}\right) - Q_y\left(Q_{\text{c}}\right) = 0 \, . \tag{104}$$

Deriving the root of the equation and substituting its value into (100), (101) and (103) enables us to determine unknown variables Q_{c}, Q_{bp} and Q_y.

Consider a handling assembly with the following parameters as an example. Ejection head defined in the form of (51) has the following parameters: $E = 4$; $L_c = 1.6$; $L_d = 1$. The aerodynamic performance of the chute is $R_e = 25$.

We'll consider two cases: good sealing of the upper cowl $R_d = 25$ and mediocre sealing $R_d = 5$. We'll be measuring the negative pressure maintained in the lower cowl ($h_y = 5$, 10 and 20 Pa) as well as aerodynamic properties of the buffer chamber/partition within the range $R_y = 0 - 300$ and of the bypass duct within the range $R_{bp} = 0 - 150$ (a case of no bypass i.e. $R_{bp} = 15 \cdot 10^9$ will be included for comparison). Without bypass, the flow rate of air arriving from the inner (buffer) chamber into the outer chamber ($Q_{y\infty}$) is significantly higher than with a bypass duct installed (Fig. 9). Particularly, increasing drag of cowl partition and increasing cross-section of bypass duct ($R_{bp} < 20$) cause the flow rate Q_y to deviate even further from $Q_{y\infty}$ (Q_y is the flow rate of air entering the outer chamber with a bypass connection present).

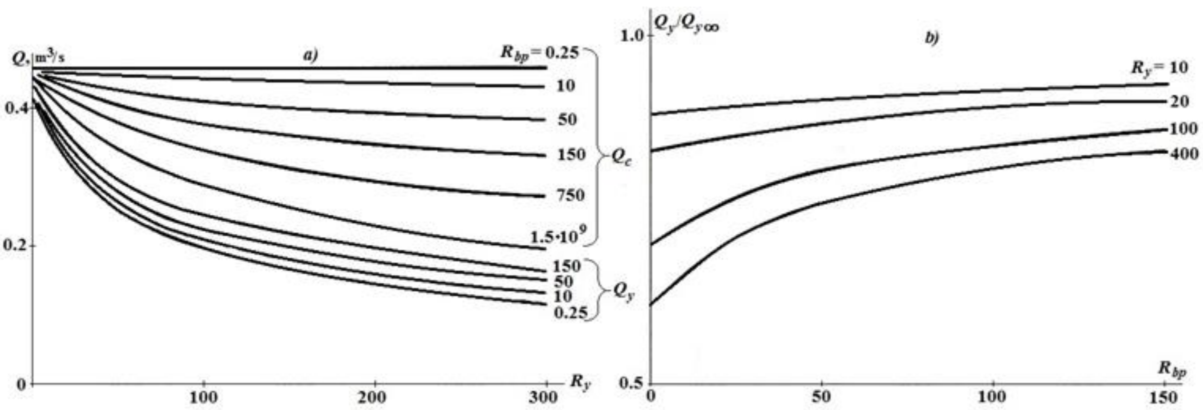

Fig. 9. Variation in air flow rates Q_y and Q_c as a function of resistances of the buffer chamber and bypass duct (with a good sealing of the upper cowl ($h_y = 5$; $R_d = 25$))

Variation of air flow rates in ducts and negative pressure in the unaspirated cowl of the feeder driving drum is indicated in Fig. 10 …14.

Curves Q_c, Q_{bp}, Q_y have been plotted using equations (101), (103) and (104), while negative pressure has been plotted according to formula (90). As these plots illustrate, the flow rate of air entering through the chute (Q_c) decreases with increasing aerodynamic performance index of the buffer chamber (Fig.10 and 11) and the bypass duct (Fig.12 and 13).

With regard to airflow in the latter (Q_{bp}) it should be noted that the flow rate increases with increasing partition drag and declines with narrowing cross-section of the bypass duct. In addition, in the case of mediocre sealing of the feeder cowl, airflow direction in the bypass duct reverses at a low drag of the buffer chamber ($R_y < 20$).

This zone expands to $R_y = 40 - 90$ with negative pressure inside conveyer enclosure increasing to 20 Pa (Fig. 14).

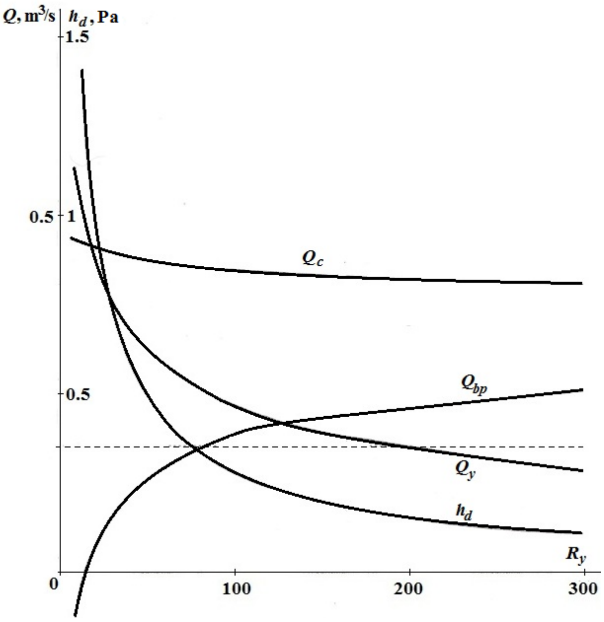

Fig. 10. Variation of air flow rates and negative pressures with increasing drag of the buffer chamber of the handling facility in the case of mediocre sealing of the upper cowl: ($R_{\text{d}} = 5; h_y = 5; R_{\text{bp}} = 25$)

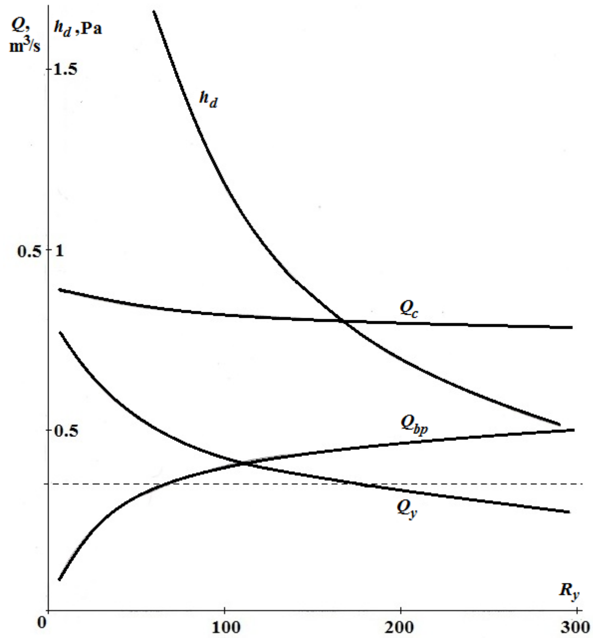

Fig. 11. Variation in air flow rates and negative pressures as a function of buffer chamber drag with a properly sealed upper cowl ($R_{\text{f}} = 25; h_y = 5; R_{\text{bp}} = 25$)

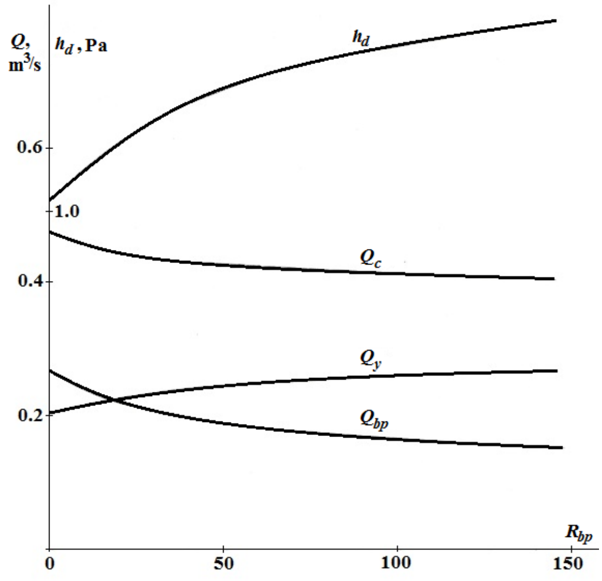

Fig. 12. Variation in air flow rate and negative pressure as a function of bypass duct drag assuming moderate pressure losses in the buffer chamber ($R_y = 100; h_y = 5; R_{\text{d}} = 25$)

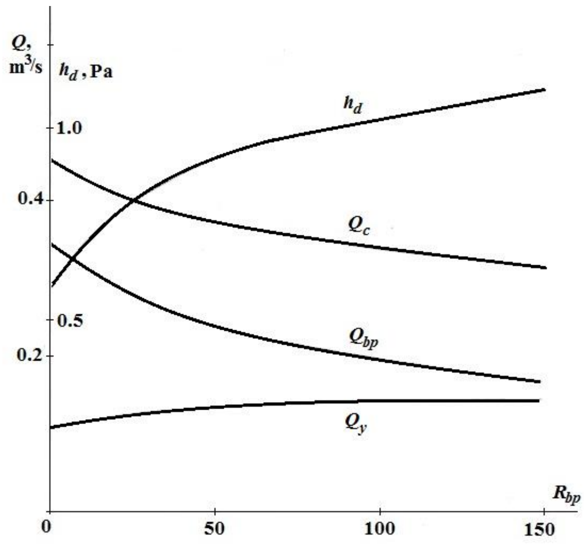

Fig. 13. Variation in air flow rate and negative pressure as a function of bypass duct drag assuming elevated pressure losses in the buffer chamber ($R_y = 400; h_y = 5; R_{\text{d}} = 25$)

This can be explained by diminishing pressure difference at ends of the bypass duct with increasing gap between cowl partition and conveyor belt. In this case the flow rate of air entering the outer cowl chamber rises above the flow rate of air in the chute ($Q_y > Q_c$).

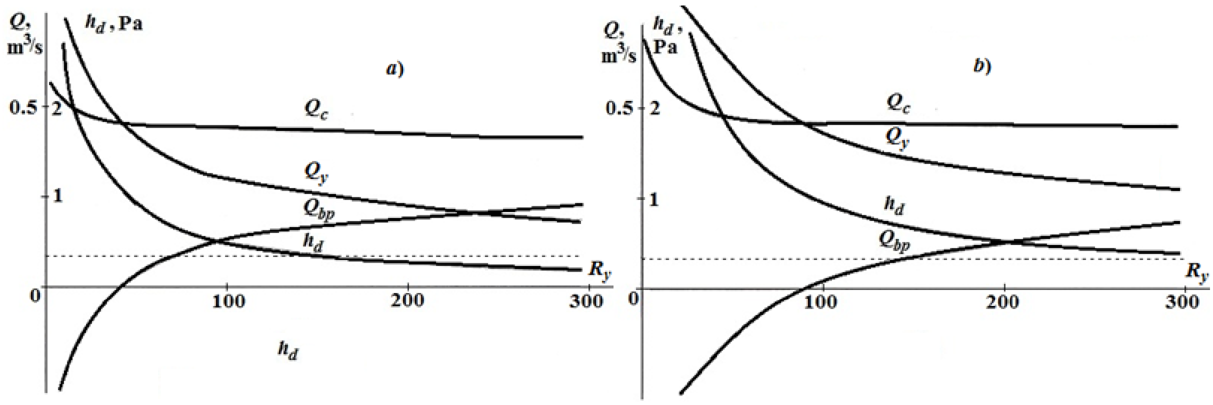

Fig. 14. Variation in air flow rates as a function of buffer chamber drag for the case of mediocre sealing of the upper cowl with increased negative pressure in the lower cowl ($R_d = 5; R_{bp} = 25;\ h_y = 10 - a;\ h_y = 20 - b$)

The bypass duct works like a channel allowing an additional volume of air in along with the main flow of ejected air. Improved feeder sealing is needed for this situation to change. As Fig. 11 illustrates, the air flow rate Q_y will be less than Q_c even if less drag is produced by the enclosure partition.

This flow rate will remain significantly below Q_c with increasing drag. At $R_y > 200$ the flow rate Q_y is reduced to almost a third of air flow rate in the chute while the flow rate of recirculated air Q_{bp} reaches 60% of Q_c. One should keep in mind, however, that the flow rate of air inside the chute is higher with a bypass duct than when a bypass duct is absent (Fig. 9 a). This happens because the bypass duct is connected in parallel and the chute-with-bypass system has a lower overall drag than any individual component of this system. As a result, when air forced by ejection, its flow rate increases similarly to the flow rate of air blown by a fan with air ducts connected in parallel. Therefore it would be more precise to compare the flow rate Q_y with the flow rate Q_c absent a bypass connection (Fig. 9 b). Thus, at $R_y = 100$ and low drag of the bypass duct ($R_{bp} = 25$) the flow rate of air entering from the bypass chamber in the case at hand will measure 70% of air velocity in the duct $Q_{y\infty}$ (absent a bypass connection $Q_{y\infty} = Q_{c\infty}$). And the flow rate of recirculated air is 30% of $Q_{c\infty}$.

Negative pressure inside the feeder cowl decreases with growing pressure losses in the buffer chamber and may become low enough for untight locations with depressed velocities to begin leaking dust into the working room due to diffusion transfer. Velocity within openings must be maintained at or above safety margin of 0.5 m/s. In this case (given a LRC 2.4 of leakage areas) negative pressure in leakage areas must not become lower than 0.36 Pa (Fig. 10, 11, 14 show the ultimate boundary of negative pressure with a dotted horizontal line). With a good seal of the feeder cowl (at $R_d = 20$) (Fig. 11–13) as well as with negative pressure inside the cowl increased to 20 Pa (Fig. 14) negative pressure within leakage areas will never fall below 0.36 Pa. Thus, it would be wise from the cost standpoint to use a bypass duct with a buffer chamber and properly sealed cowls.

4 CONCLUSIONS

- Aspiration volumes in the classical aspiration layout for elevator handling of grain are determined by balance equations (73) and (74). Basic components of both equations comprise volumetric flow rates of air entrained into aspirated cowls through leaking joints and process openings by the negative pressure (maintained inside cowls by an aspiration unit) and flow rates of air transferred in ducts.
- Flow rates of transferred air Q_0, Q_1, Q_2, Q_3 may be determined using algorithms (Fig. 4) devised by solving combined non-linear equations (69)-(72) with a joint use of iteration and bisection methods.
- An analysis of computation results for an exemplary ("standard") assembly shows that increasing negative pressure inside the boot cowl and decreasing leakage area in the cowl of elevator head both produce increasing negative pressure in the head cowl (h_s), causing flow rates of ejected air to increase in the loading chute (Q_0, Fig. 5) and to decrease in the discharge chute (Q_3, Fig. 6). Total air flow rate in the elevator enclosures $(\Delta Q = Q_2 - Q_1)$ varies similarly, rising with increasing h_b and declining with increasing R_s. Specific regularities of air cross-flow in ducts also affect aspiration volumes: the required air flow rate in the local suction unit of elevator boot cowl (Q_e) increases while the volume of aspiration from the upper conveyor cowl (Q_a) decreases with increasing h_b (Fig. 7 a), whereas both flow rates decrease with increasing sealing degree (Fig. 7 b). However the total flow rate of aspirated air remains sufficiently high: even with a small negative pressure inside the boot cowl $(h_b = 16.8 \text{ Pa})$ and adequate sealing of the elevator head cowl $\left(R_s = 14.4 \text{ Pa}/\left(\text{m}^3/\text{s}\right)^2\right)$, the total aspiration volume for the exemplary assembly would be about 2.06 m^3/s.
- The necessary design performance of aspiration system may be reduced not only by reducing the optimum negative pressure in cowls and their sealing but also by using bypass channels to enable closed-loop circulation of ejected air.
- Regularities of air cross-flow and circulation patterns in conveyor-to-conveyor grain handling with a bypass duct connecting the inner chamber of a double-walled cowl with the cowl of the driving drum (Fig. 8) can be studied using equations for pressure losses in ducts (86)-(90) and air flow rate balance equations for cowls and junction points (91)-(93). Analysis of these regularities has shown that efficient operation of the bypass duct requires negative pressure inside the cowl of the upper unaspirated conveyor to exceed the negative pressure in the buffer (inner) chamber (96) or (98). This chamber improves the reliability of bypass operation with a circulation layout as opposed to a parallel cross-flow layout whereby total flow rate of incoming air from the upper cowl into the lower cowl would increase, leading to higher required aspiration volumes.
- An analysis of the numerical solution for equations (104) in view of (103) for the exemplary conveyor handling facility indicates that, absent bypass, the flow rate of air coming in from the inner chamber into the outer chamber of a double-walled cowl $Q_{y\infty}$ is significantly higher than when the assembly is furnished with a bypass duct (Q_y). With increasing drag of inner cowl walls as well as increasing cross-sectional area of the bypass duct $(R_{bp} < 20)$, flow rates Q_y and $Q_{y\infty}$ deviate further apart (Fig. 9).

The flow rate Q_{bp} of air entering through the bypass duct of a handling facility increases with increasing drag of the buffer (inner) chamber ad decreasing drag of the bypass duct (Fig. 10 and Fig. 12). When the upper (unaspirated) cowl is poorly sealed $\left(R_d \le 5\,\text{Pa}/\left(\text{m}^3/\text{s}\right)^2\right)$ and partitions have a low drag $\left(R_y < 20\,\text{Pa}/\left(\text{m}^3/\text{s}\right)^2\right)$, airflow in the bypass duct may reverse its direction $\left(Q_{bp} < 0\right)$. The zone of negative airflow in the duct extends to $R_y = 40-90\ \text{Pa}/\left(\text{m}^3/\text{s}\right)^2$ when negative pressure inside the conveyor cowl increases to 20 Pa (Fig. 14). To prevent the occurrence of such a zone, sealing of the upper cowl must be improved (Fig. 11). As the drag of the buffer chamber increases (with $R_y > 200\ \text{Pa}/\left(\text{m}^3/\text{s}\right)^2$), flow rate of recirculated air Q_{bp} reaches 60% of Q_c.

The flow rate of air Q_c coming in through the chute in the presence of a bypass connection is greater than the flow rate $Q_{c\infty}$ of air in the same chute absent bypass (Fig. 9a). This is because ejection head building up inside the chute acts like a blower (fan) for a parallel network of two ducts – the bypass duct and the gap between the inner cowl walls and the conveyor belt of the upper conveyor, with a combined drag lower than they would be the case for either duct individually. Therefore the relation $Q_{bp}/Q_{c\infty}$ would be more fitting to describe the degree of recirculation in the bypass duct.

- The effect of reducing aspiration volumes for a handling facility equipped with a bypass duct is maximized by ensuring proper sealing of ducts and designing for a buffer channel with increased drag in the inner cowl. In the example considered earlier, at $R_y = 100\ \text{Pa}/\left(\text{m}^3/\text{s}\right)^2$ and a bypass duct with a low drag $R_{bp} = 25\ \text{Pa}/\left(\text{m}^3/\text{s}\right)^2$, air flow rate Q_y would make up 70% of $Q_{c\infty}$, i.e. decrease 1.428 times compared to the case of an unbypassed assembly.

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REFERENCES

[1] O.A. Averkova, I.N. Logachev and K.I. Logachev, Ejecting properties of a bucket elevator. *V International Conference on Particle-based Methods. Fundamentals and Applications (PARTICLES 2017)*, pp. 45–56, 2017.

[2] O.A. Averkova, I.N. Logachev and K.I. Logachev, *Cross-flow of air through sealed elevator enclosures. V International Conference on Particle-based Methods. Fundamentals and Applications (PARTICLES 2017)*, pp. 33–44, 2017.

[3] I. N. Logachev and K.I. Logachev. *Industrial Air Quality And Ventilation: Controlling Dust Emissions*. Boca Raton: CRC Press, 2014.

[4] I. N. Logachev, K. I. Logachev and O.A. Averkova. *Local Exhaust Ventilation: Aerodynamic Processes and Calculations of Dust Emissions.* Boca Raton: CRC Press, 2015.