Proposal of a Pneumatic Transport System in Aspiration based on Steam Jet Ejector

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Abstract: Pneumatic transport is a well-known and widely applied system for transporting materials in dust or grain conditions. In the last years, no improvements have been done regarding pneumatic transport systems, for which the design main characteristics have remained substantially unchanged: a blower placed either upstream (in pressurized plants) or downstream (in depressurized plants) of the silos containing the material generates the motion of the same, while a separator opportunely designed (often a cyclone) provides the separation between the air stream and the material in correspondence of the discharge point.

In this paper, an improvement to the aspiration pneumatic system is proposed. The blower is substituted by a steam jet ejector placed immediately downstream of the air-material separator and filter. Feeding the ejector inlet with steam having the opportune pressure and flow-rate, the blower can be eliminated. The ejector outlet port, which is crossed by a mixture of steam and air, needs to be followed by a condenser to allow the recycling of the water used for generating the steam, and by an air extractor to exhaust the air employed in the transport.

In the paper the feasibility of the plant is discussed together with its advantages compared to the classical solution providing blowers as material prime movers. One particular advantage is the lack of moving parts, which improves the plant reliability. Another advantage is the possibility to integrate the system with the steam produced by a steam turbine cycle and the possibility to employ the plant in modular stations, in order to increase the transport distance. Moreover, a comparative analysis with the classical solution is carried out in terms of economical feasibility.

Keywords: Pneumatic plants, Steam jet ejectors, Material convey, Economical feasibility

I. INTRODUCTION

Pneumatic conveyors are widely used for transporting several types of bulk materials with the advantage of ensuring a clean environment, as the material is confined within a pipeline, travelling together with air which behaves as motor fluid; the mixing and separation between air and material are demanded by particular components i.e., respectively, injectors and separators.

Two main different types of pneumatic systems are possible: the pressurized one, in which a blower placed upstream of the material injection point produces the stream of air required to exert the motion of the material particles; and the aspiration type, where the blower is placed at the exit of the plant and the pipelines are at a pressure lower than atmospheric. Each of these solutions has its strengths and weaknesses; for example, the pressurized one is good for long distances but suffers from problems of material injection in the circuit and is good for feeding many material exit locations from just one material entrance point; instead, the depressurized system is suitable only for short paths but has lower pressure losses in the circuit, owing to the lower pressure and density of the air crossing its tubes, and is more suitable to feed one material outlet point from many inlet locations.

However, in the latest years, the afore mentioned schemes have never been changed significantly, maintaining practically unvaried the design and the functioning principles of the system.

In this paper, the authors aim to propose a new possibility of exploiting an aspiration pneumatic conveyor system, by substituting the downstream blower by a steam jet ejector to be fed by the steam conveyed from a bleeding of a back-pressure turbine. The steam jet ejector, placed immediately downstream of the filter after a cyclone-shaped separator, fed by a correct pressure and temperature value of the motor steam, is able to produce the required depressurization in the pneumatic aspiration plant, while the steam jet ejector outlet port is followed by a condenser and deaerator, to recover the condensed motor steam while expelling into the atmosphere the air used for the transport.

The paper is organized in the following sections:

Section 2 provides the literature review regarding pneumatic conveyors and steam jet ejectors.

Section 3 describes the proposed aspiration plant enhanced by steam jet ejector providing, the proper drawings for better comprehension.

Section 4 proposes a comparison between two plants: one characterized by a steam boiler feeding a back-pressure turbine intended to produce electric energy combined with the heat coming from the steam leaving the back-pressure turbine. Moreover, the plant needs to transport a certain amount of solid material (concrete in dust) by means of an aspiration pneumatic plant fed by a classical electrically powered blower; the other plant of the comparison bleeds part of the steam at the exit of the back-pressure turbine in order to feed the steam jet ejector employed to generate the depressurization required for the pneumatic transportation.

Section 5 contains the results of the calculations for the two proposed cycles.

Section 6 compares the results found for the two cycles in economical terms to highlight the convenience of the proposed solution.

Section 7 presents the conclusions of the paper.

II. LITERATURE REVIEW

A. Literature review on pneumatic conveyors

As previously mentioned, the papers findable in literature regarding pneumatic conveyors do not focus on any type of plant improvement from the point of view of the design or of the operational principle. In particular, can be found numerical and experimental studies for flow improvement and studies regarding accessories e.g. for feeding the material to the plant.

In [1] can be found a study regarding the numerical analysis by Computational Fluid Dynamics (CFD) of the behaviour of flexible (non-rigid) biomass particles along the pipelines.

In [2] the stability of a high pressure pneumatic transport is plant investigated by an experimental facility to test the transport of a mixture of pulverized coal and liquefaction residues of a coal gasifier.

In [3] is proposed a method for calculating the pressure loss of the pneumatic system of a cotton harvester related to the power consumption of the fan drive, by mathematical models and numerical studies.

In [4] a pneumatic unloader is developed for building material binders in mine workings. In the paper, a lifting device is proposed to increase pneumatic transport productivity and efficiency by reducing blockage in the lower part of the pipeline.

In [5] a study is proposed regarding ceramic rotary valves for feeding the material to the main pneumatic transport pipeline. The study claims that, substituting a screw pump with a ceramic rotary valve there can be an energy saving up to 97.5%.

In [6] is provided an experimental study regarding the breakage of wood pellets in pneumatic conveyor plants, changing the air feeding pressure and the particles size. The results of the tests provide insights in evaluation of pneumatic pipe design and construction.

B Literature review on steam jet ejectors

From the point of view of steam jet ejectors, in literature can be found articles regarding numerical modellings and experimental analyses, both for normal jet units and for variable geometry motor fluid jet units.

In [7] is presented a one-dimensional ejector model based on real compressible fluid properties, which can be used to efficiently design a steam jet ejector.

In [8] is presented a steam jet ejector for desalination plants. The study focuses on geometry modifications of the ejector by means of computational fluid dynamics simulations, varying the operating temperature of the primary (motor) fluid and the position of the supersonic nozzle, in order to increase the entrainment ratio (see after) of the ejector.

In [9] a theoretical calculation method, very easy and straightforward to follow, is presented for designing steam jet ejectors for refrigeration applications. The method is validated by experimental tests.

In [10] an innovative application for a nuclear plant is proposed, by coupling a steam jet ejector to the recirculation of a stream of steam in an external boiling system for the secondary loop of a nuclear power plant.

Article [11] presents another mathematical modelling to predict the performance (in particular the entrainment ratio) of steam jet ejectors, introducing corrections based on measurements on high efficiency industrial components.

III. THE PROPOSED NEW SYSTEM

As previously described in the introduction, the proposed innovative pneumatic system is based on the substitution of the classical blower of the aspiration pneumatic plant by a steam jet ejector able to produce, thanks to a stream of motor steam, the required depressurization for providing the motion of the material. A steam jet ejector is composed by three main elements

A supersonic nozzle, which provides the stream of motor steam, pushed at supersonic speed into a volume called "steam chest", where occurs the first meeting with the entrained fluid.

A mixing chamber, in which the motor fluid and the entrained fluid are mixed together; often, this zone is characterized by the presence of shock waves which, increasing entropy, are cause of efficiency losses of the system.

A diffuser, in which the mixed fluids stream is slowed down to the discharge speed; also this component is characterized by entropy increase and efficiency losses.

The system proposed in this article employs the stream of motor steam to aspirate the air coming from the plant, as depicted in Fig. 1; so, the ejector inlet port of the entrained fluid (air) is placed immediately downstream of the filter unit which stands after the last separation cyclone of the pneumatic plant. In order to recover the motor steam, the plant requires an additional component, i.e. a condenser, which operates also as separation unit between the air and the steam; in fact, as depicted in Fig. 1, the condenser is equipped with an outlet tube exhausting the air into the atmosphere.

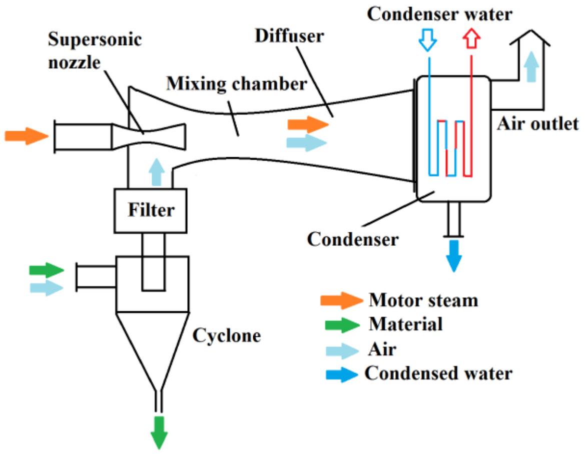

Fig. 1.Sketch of the proposed ejector system for aspiration pneumatic plants.

The pneumatic transport aspiration system equipped with steam jet ejector has the main benefit of avoiding the presence of rotary machinery for the motion of the material, increasing the plant reliability.

The main drawback is the limited depressurization with respect to a pressurized pneumatic transport plant, which translates into a limited distance that can be covered by the transportation plant. A possible solution may be the implementation of modular depressurization stations, as depicted in Fig. 2.

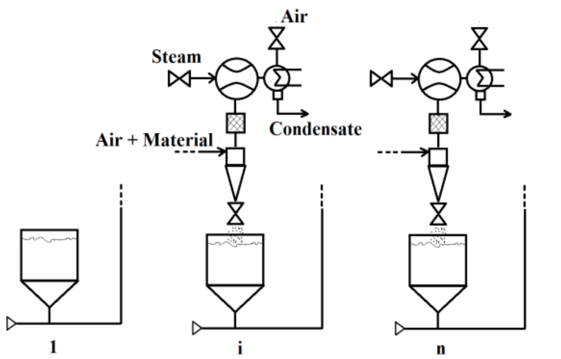

Fig. 2.Sketch of the modular depressurization stations equipped with steam jet ejector.

IV. COMPARISON BETWEEN THE TWO SYSTEMS

The pneumatic transport system equipped with steam jet ejector has the necessity of a low cost steam source, such as the bleeding from a back-pressure steam turbine finalized to feed a heating process after the expansion.

Therefore, in this section a comparison is presented between two coal fired steam plants finalized to provide a steam flow rate to a heating process hypothesized as equal to 14 kg/s at a pressure of 5 bar and a temperature of 152°C (which corresponds to saturated steam conditions).

Moreover, these two plants are studied under the hypothesis to need the transport of a flow rate of concrete in dust of 39.4 t/h, which can be done either with the classical pneumatic system in aspiration or with the transport system equipped with steam jet ejector.

In Fig. 3 and Fig. 4 are presented the thermodynamic cycles of the two plants in the (T, S) diagram: the basic cycle, not presenting the enhancement of the steam jet ejector (Fig. 3) and the one equipped with steam jet ejector (Fig. 4). Table 1 presents the cycles’ values.

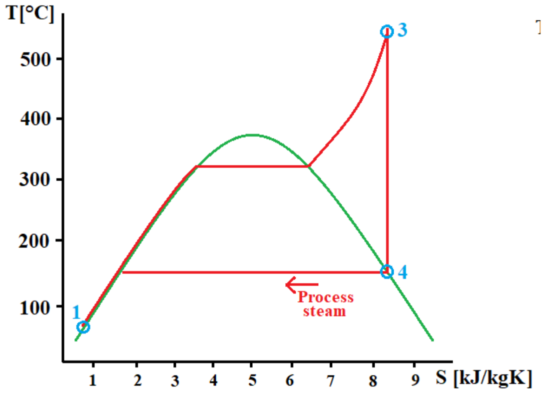

Fig. 3.(T, S) diagram of the basic steam cycle equipped with back pressure turbine for the process steam.

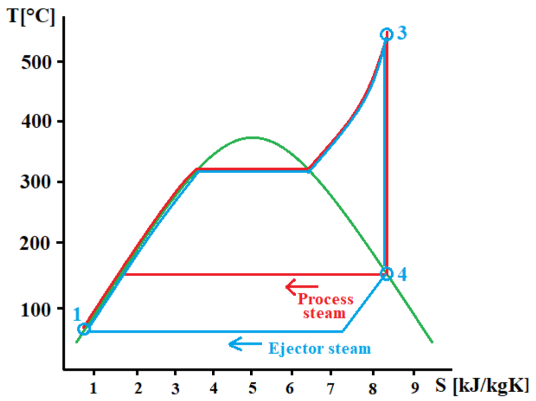

Fig. 4.(T, S) diagram of the steam cycle equipped with back pressure turbine and steam jet ejector.

TABLE I
CHARACTERISTICS OF THE STEAM CYCLE

Description	Value	[Units]
Inlet water temperature	20	[°C]
Enthalpy at point 1 (h_1)	91.4	[kJ/kg]
Cycle maximum pressure	80	[bar]
Cycle maximum temperature	550	[°C]
Enthalpy at point 3 (h_3)	3521.7	[kJ/kg]
Process and ejector motor fluid steam pressure	5	[bar]
Process and ejector motor fluid steam temperature	152	[°C]
Enthalpy at point 4 (h_4)	2748.5	[kJ/kg]

V. RESULTS

The pneumatic transport is hypothesized to convey a flow rate of concrete dust of 39.4 t/h. Such material has a bulk density of 1400 kg/m^3, therefore requiring, for being pneumatically transported, a flow rate of air which can be calculated by the semi-empirical formula in Equation 1 (Hudson formula):

$$Q = 0.116\, \rho\, T \qquad (1)$$

Where Q is the flow rate of air in Nm^3/h, ρ is the material density and T is the flow rate of material in t/h. From this formula, it appears a required air flow rate for the pneumatic transport equal to 6398.6 Nm^3/h, corresponding to 1.78 Nm^3/s, or 1.135 kg/s.

Moreover, for the pneumatic transport system is hypothesized an overall pressure loss of 0.5 bar from the air inlet filter down to the last material filter, including all the pressure losses owing to the material mixing and transport.

In order to make possible the extraction of such air flow rate by means of a steam jet ejector, this component needs to be fed by a steam flow rate which is calculable by the component's entrainment ratio (*ER*), defined as in Equation 2:

$$ER = m_{\,entrained\,fluid} / m_{\,motor\,fluid} \qquad (2)$$

Where $m_{\,entrained\,fluid}$ and $m_{\,motor\,fluid}$ are expressed in kg/s.

In this context, it was decided to choose an optimized industrial ejector presented in [11], with a pressure of the motor fluid equal to 5 bar, able to provide an aspiration pressure in the air inlet port of 0.5 bar and presenting an entrainment ratio equal to 0.81; this means that the mass flow rate of steam which needs to be fed to the ejector is equal to 1.4 kg/s. Such steam flow rate must be added to the flow rate circulating in the coal fired cycle, so expanding in the turbine and producing extra work. This is visible in Fig. 4, in which the two steam flow rates, that for the process and that for the ejector, are represented in different colours.

Regarding the pneumatic plant actioned with the classical blower, it is possible to calculate the electric power consumption by employing the known formula

$$P_{el} = (m_{air}\, c_p T_1/\eta)(\beta^{(k-1)/k}-1) \qquad (3)$$

Where

m_{air} is the flow rate of the air crossing the blower.

c_p is the air specific heat capacity equal to 1.005 kJ/kgK

T_1 is the air inlet temperature.

η is the global efficiency of the blower defined as ratio between the power effectively provided to the air stream and the absorbed electric power.

$\beta = p_{outlet} / p_{inlet}$ is the pressure ratio of the blower, in this case it is equal to about 2 .

k is the ratio between constant pressure and constant volume specific heat capacities for air, equal to 1.4.

From this calculation, the blower consumes an electric power of 91.7 kW.

VI. DISCUSSION

In this section the two complete cycles are compared from an economical point of view in order to investigate the convenience of the steam jet ejector solution over the classical solution for the pneumatic transport.

To do this, it is required to calculate the cost of the sold electric power and the cost of the coal employed to fire the steam boiler.

The power for the superheated steam production in the boiler and the power extracted from the turbine depend from the enthalpy values of the cycle points 1, 2 and 3, which are indicated in Table I; the power provided to the steam in the boiler depends from the quantity (h_3 – + h_1), multiplied by the passing flow rate i.e. 14 kg/s for the normal cycle and by 15.4 kg/s for the cycle equipped with steam jet ejector.

$$P_{thermal} = m_{fluid}\,(h_3 - h_1) \qquad (4)$$

The power extracted from the turbine depends on the quantity $h_3 - h_4$, always multiplied by the respective flow rates of the two cycles and of course by the turbine and alternator efficiency, which was set to 0.95 (η_g).

$$P_{electric} = \eta_g\, m_{fluid}\,(h_3 - h_4) \qquad (5)$$

Moreover, it is necessary for a thorough economical comparison, to know the flow rate of coal employed to fire the boiler in the two cases; this can be determined from $P_{thermal}$ by knowing the lower heating value of the coal, which is 29.6 MJ/kg.

Finally, it is necessary to provide sensate price values both for electric power and for coal; in particular, the price of coal was set to 400 \$/t, corresponding to 0.36 €/kg and the price of electric energy was set to 0.28 €/kwh.

In Table II is visible a comparison between the traditional plant and the steam jet ejector plant on the basis of thermal power required from the boiler, coal flow rate, electric power produced and blower power.

TABLE II
THERMAL POWERS, ELECTRIC POWERS AND COAL MASS FLOW RATES FOR THE TWO CYCLES

	Value	**[Units]**
Traditional plant		
Thermal power required	48024.9	[kW]
Coal flow rate	1.62	[kg/s]
Electric power produced	10284.4	[kW]
Blower power	91.7	[kW]
Steam jet ejector plant		
Thermal power required	52827.4	[kW]
Coal flow rate	1.78	[kg/s]
Electric power produced	11312.9	[kW]

The costs in €/s regarding coal and electricity and the revenues, always in €/s of selling electricity can be determined by multiplying the prices before established by, respectively, the kW of electric power and the flow rates in kg/s of coal before calculated. The comparison between the two systems in terms of revenues and costs are presented in Table III

TABLE III
COMPARISON OF COSTS AND REVENUES FOR THE TWO CYCLES

	Electric Energy Sold [€/s]	Coal cost [€/s]	Blower energy [€/s]	**TOTAL INCOME [€/s]**
Traditional plant	+ 0.80	– 0.58	– 0.007	**0.21**
Steam jet ejector plant	+ 0.88	– 0.64	0.00	**0.24**

As visible, the steam jet ejector system allows to obtain a higher revenue (about 13%) compared to the plant equipped with the classic system, due to the fact that a higher circulating steam flow rate in the cycle produces a higher amount of electric power which can be sold.

VII. CONCLUSIONS

This paper presented an innovative system for an aspiration pneumatic transport of bulk material, characterized by the substitution of the classical aspiration blower by a steam jet ejector. Such ejector can be fed by a steam bleeding coming from a turbine, and presents as main advantage the absence of parts in motion, so increasing the reliability of the entire system.

In the article, the system was described by drawings and compared to a classical aspiration pneumatic transport system moved by a blower, by introducing a comparison based on similar conditions (the presence of a required steam amount for a thermal process and of a back-pressure steam turbine cycle).

The comparison results indicate that the system equipped with steam jet ejector produces a higher revenue in terms of sold electric power owing to the larger amount of steam circulating in the turbine cycle. Future work will further develop the proposed concept, keeping into account the requirement of cleaning the condensed water downstream of the ejector.

REFERENCES

[1] Markauskas D., Platzk S., Kruggel-Emden H., 2022, Comparative numerical study of pneumatic conveying of flexible elongated particles through a pipe bend by DEM-CFD, Powder Technology, 399, 117170.

[2] Peng, B.Z., Fang X.H., An H.Q., Liu Z., Li Y., Feng Z.Y., 2022, Study on the Stability of High Pressure Pneumatic Transport of the Mixture of Pulverized Coal and Extraction Residue of Direct Coal Liquefaction Residue, Environmental Science and Engineering, pp. 1075 – 1084.

[3] Matchanov R., Rizaev A., YuldashevA., Kuldoshev D., Mirzaeva M., 2021, Methods for calculating the pressure loss of the air flow and energy consumed by the fan of the cotton harvester, E3S Web of Conferences, 264, International Scientific Conference on Construction Mechanics, Hydraulics and Water Resources Engineering, CONMECHYDRO 2021, Tashkent, 1-3 April 2021.

[4] Davydov S.Y., Apakashev R.A., Valiev N.G., Kostyuk P.A., 2021, New Developments in Pneumatic Delivery of Building Material Binders and Inert Additives, Refractories and Industrial Ceramics, 61(6), pp. 626-630.

[5] Dikty M., Rieck T., 2021, Operating experience with over 100 ceramic rotary valves for pneumatic transport, Cement International, 19 (1) pp. 34–39.

[6] Abdulmumini M.M., Zigan S., Bradley M.S.A., Lestander T.A., 2020, Fuel pellet breakage in pneumatic transport and durability tests, Renewable Energy, 157, pp. 911-919.

[7] Kitrattana B., Aphornratana S., Thongtip T., 2021, One dimensional steam ejector model based on real fluid property, Thermal Science and Engineering Progress, 25, 101016.

[8] Shahzamanian B., Varga S., Soares J., Palermo-Marrero A.I., Oliveira A.C., 2021, Performance evaluation of a variable geometry ejector applied in a multi-effect thermal vapor compression desalination system, 195, 117177.

[9] Ruangtrakoon N., Aphornratana S., 2019, Design of steam ejector in a refrigeration application based on thermodynamic performance analysis, Sustainable Energies Technology and Assessments, 31, pp. 369-382.

[10] Damiani L., Revetria R., 2015, New steam generation system for lead-cooled fast reactors, based on steam re-circulation through ejector, Applied Energy, 137, pp. 292-300.

[11] Friso, D. Mathematical Modelling of the Entrainment Ratio of High Performance Supersonic Industrial Ejectors. Processes 2022, 10, 88. https://doi.org/10.3390 pr10010088.