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Use of Gas-Solid-Ejectors as Inward Transfer Units for Pneumatic Conveying of Bulk Solids

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1. Introduction

Ejectors have been used industrially for more than 150 years. Way back in 1820 Stephenson was building ejectors into the funnels of steam locomotives in order to enlarge the draft of the flue gas discharge. Around the same time elsewhere ejectors (of gas-gas or fluid-gas type) were being used as jet pumps to convey water (Thompson, 1852), by Bunsen to create a vacuum, and in the form of ejector gas burners. Dencker (1928) was the first to investigate the possible use of ejectors in pneumatic conveying for the inward transfer of hay and straw in agricultural engineering [1].

In view of their many advantages, ejectors have since become a firmly established part of pneumatic conveying technology.

However, ejectors cannot be used indiscriminately; the indisputable advantages will depend specifically on the material to be conveyed, plant design and air supply. This article will describe how ejectors can be used in practice, the difficulties which may arise if ejectors are used for the wrong assignments and how these undesirable effects may be eliminated or avoided.

The article will focus on the use of gas-solids ejectors as used in power generation and environmental protection technology. Air is used exclusively as the carrier medium. The examples given are typical, however, of the entire range of applications and are intended to illustrate the advantages and disadvantages of ejectors in general by way of individual case examples.

State-of-the-art ejector design will be the subject of a later publication. This present article is intended more to concentrate on practical problems and their solution from the point of view of operators and planners of pneumatic conveying plants.

This article has been written for:

- operators encountering difficulties with a normal pneumatic rotary conveying system (leakage air dissipation, build-up of material in front of the rotary valve, insufficient conveying performance, high wear on the rotary valve, production standstills etc.)
- operators and planners seeking to transport small quantities of material reliably over small distances by pneumatic means
  - particularly if continuous conveying is necessary
  - in the case of dusts which cake and stick
  - at high temperatures
  - where leakage air cannot be permitted to arise in the material feed section
- operators and planners seeking to achieve additional technical objectives (e.g. inward transfer of solids into combustion plants or flue gas ducts to reduce pollutants in flue gases etc.)
- operators with an ejector conveying system not working to complete satisfaction.

2. Inward Transfer Units (Feeders) in Pneumatic Conveying Systems

In all systems which pneumatically convey material of any type, the flow pressure loss of the gas/solids mixture at the start of the conveying line causes positive pressure to be created against the material to be fed into the system. The most well known inward transfer units for continuous pneumatic conveying and at lower conveying pressures of up to approximately 1 bar positive pressure are as follows:

- rotary valve (with horizontal and vertical rotational axis)
- screw pump (Fuller, Möller or Peters pump).

A pressure vessel is normally used if material is to be conveyed against even higher pressures at the start of the line. Fig. 1 shows equipment and ejector in diagrammatic form.

All the above inward transfer units (feeders) ensure correct conditions for the incoming material by means of static pressure, i.e. the full conveying pressure is applied to the respective sealing elements. During the course of operation (and thus given persistent wear), this leads to leakages at the inward transfer unit and to the escape of leakage air, as shown in Fig. 1. However, as will be illustrated in more detail below, leakage air is the main cause of virtually all faults.

The ejector is different: in this system, sealing is achieved by means of the dynamic pressure of the carrier jet, which inwardly transfers the material into the line. If the ejector has been dimensioned correctly, a slight negative pressure will always be present at the feeding point. This reliably avoids leakage air.

Fig. 2 shows the pressures prevailing in a pneumatic conveying system (rotary valve conveying, ejector conveying). It can be seen that in the case of rotary valve conveying, the full static pressure from the conveying line in the feed area is beneath the rotary valve whilst even a slight negative pressure (suction effect) can be achieved if an ejector conveying system is used.

Conveying by means of rotary valve, particularly of fine dusts, creates difficulties with subsequent flow and filling of the ro-

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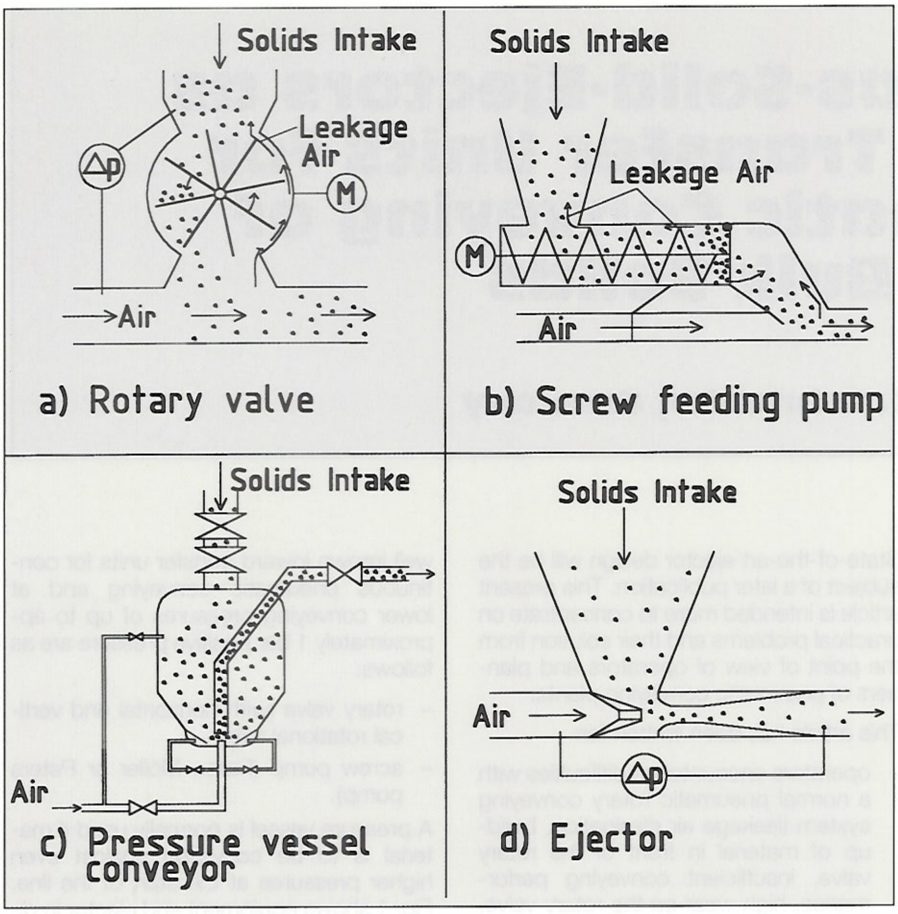
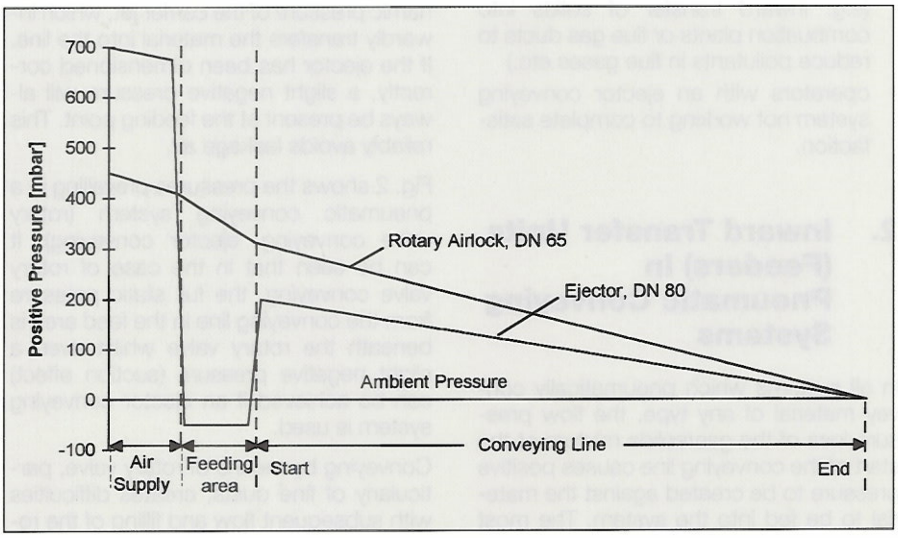


Fig. 1: Different inward transfer units (feeders)

tary valve pockets, which may lead to the complete breakdown of the conveying process. The leakage air (Fig. 1) causes the fine particles to float, form bridges over the inlet port, thus preventing dust discharge.

As Fig. 3 shows, the quantity of leakage air can be considerable. The figure shows the leakage air volume flow for different sizes of rotary valve (DN150, DN250, DN450) and clearances of 0.2 mm (slight wear) and 0.5 mm (increased wear) as a function of the prevailing pressure. Assuming a positive pressure of 400 mbars (corresponding to a pressure ratio of 1.4), a leakage air volume of approximately 1 m^3/min is to be observed in a valve of DN 250 and a clearance of 0.2 mm. If wear causes the clearance to increase to 0.5 mm, the volume flow of leakage air will increase to approximately 3.5 m^3/min and the entire feed hopper may be fluidized depending on material characteristics.

Fig. 2: Positive pressure development along the conveying line



By contrast, a negative pressure is created in the feed hopper of an ejector system or air with material taken in, thus preventing the creation of any leakage air. The faults described, such as air blowing back into the hopper, blocking of the material feed etc., can be eliminated completely. The material feed from the dosing unit to the ejector can even be improved by correctly positioning the check valve.

The ejector also has the following important advantages:

- Metered infiltrated air intake (check valve) enables caking in the feed to be avoided or promotes the infeed of material with small particle sizes, i.e. the material is sucked into the ejector.
- Ejectors require little maintenance, i.e. apart from a visual inspection (negative pressure in housing), no further maintenance is necessary.
- Conveying with ejectors is continuous; the material flow is not stopped or interrupted.
- Ejectors do not contain any moving parts and are also suitable for high temperatures.

3. Design of an Ejector

Fig. 4 shows the design of an ejector (basic form). The ejector contains no moving parts (with the possible exception of a check valve). It essentially consists of the following:

- Housing ①
- Injection nozzle (exchangeable) with assembly (adjustable) ②
- Fluidizing bottom ③
- Manual adjuster for fluidizing bottom ④
- Mixing pipe with capture nozzle and diffusor ⑤
- Connection for conveying line ⑥
- Manometer ⑦
- Buffer tank / Hopper ⑧
- Check valve ⑨
- Door (e.g. for service or calibration of the dosing unit) ⑩
- Dosing unit (e.g. screw feeder) ⑪.

The most important components are briefly described in the following.

3.1 Carrier Nozzle and Feed Hopper

The air jet is accelerated in the carrier nozzle to high velocities (up to a maximum of the velocity of sound, and even higher in Laval nozzles), thus converting the potential energy of the air jet into kinetic energy. The incoming jet enters the capture nozzle and the mixing pipe at ambient pressure.

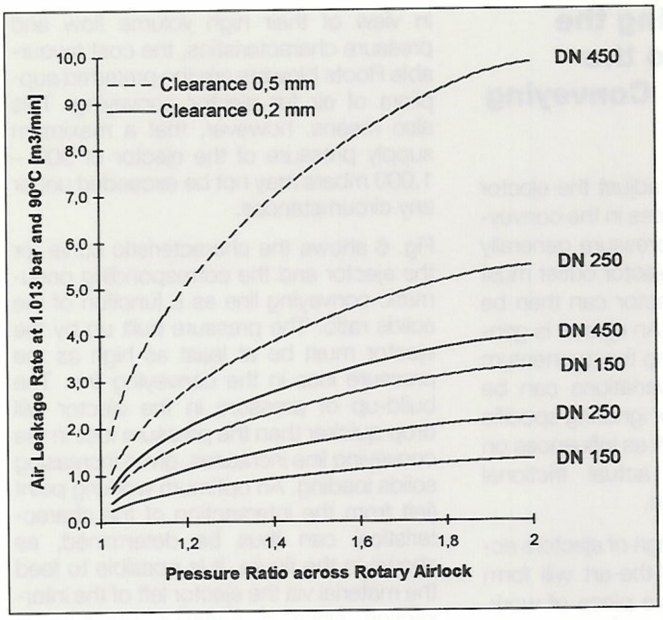


Fig. 3: Air leakage rates for different sizes of rotary airlocks as function of pressure ratio

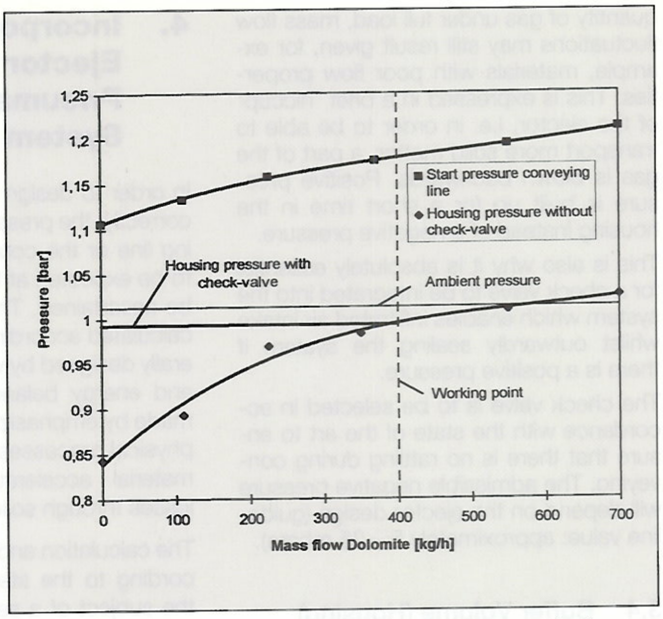
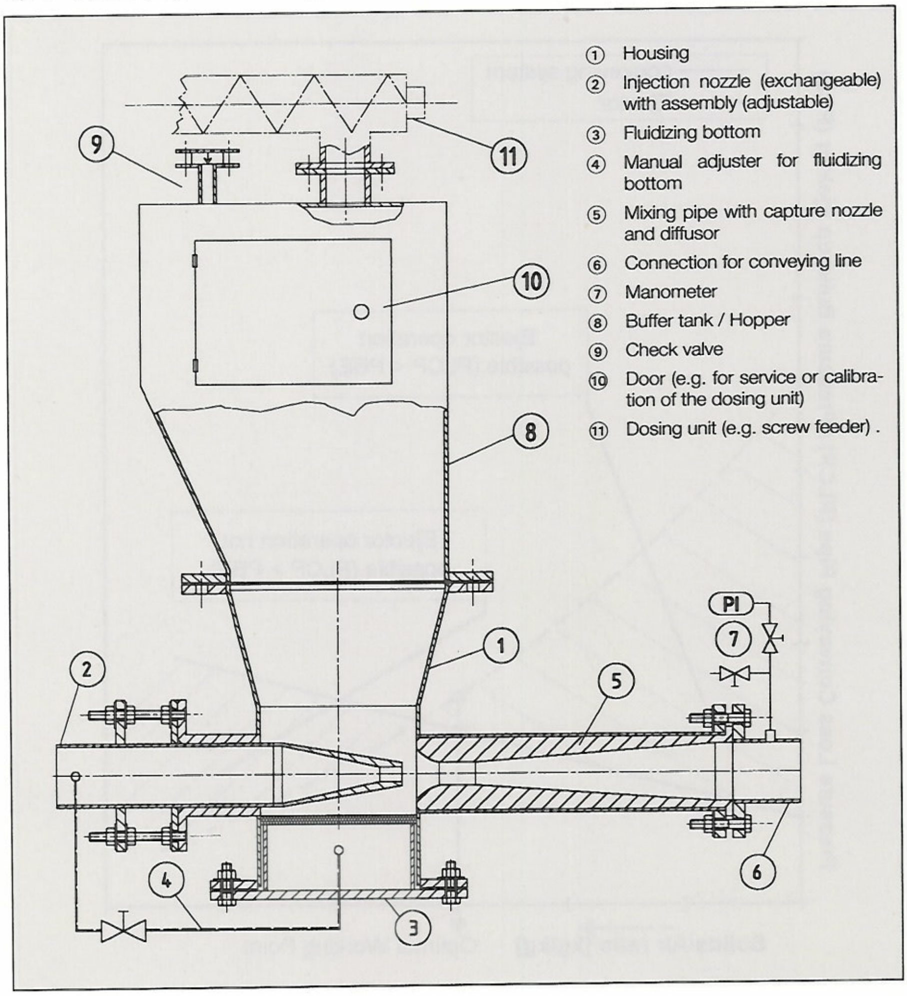


Fig. 5: Pressure development in ejector housing and initial conveying line pressure depending on mass flow of dolomite

This means that the material fed through the feed hopper can be transferred to the conveying line without any additional mechanical sealing. In order to avoid the discharge, in particular of dust particles, through this hopper, the ejector must be designed in such a way that even at nominal power a small additional gas jet is taken in from the environment.

Fig. 4: Ejector design with buffer hopper



3.2 Mixing Pipe and Diffusor

The incoming jet is delayed again in the mixing pipe and the kinetic energy is reconverted to potential pressure energy with considerable losses. A part of this energy is used for the acceleration of the solids and of the infiltrated air volume which has also been sucked in.

The diffusor cuts the velocity of the air jet back to that prevailing in the subsequent conveying line system, thus serving to recover more pressure.

Injection nozzle, mixing pipe diameter and length as well as diffusor must be carefully harmonised and matched to the material in order to achieve as high a degree of ejector efficiency as possible.

3.3 Check Valve

The check valve to which reference has already been made serves the intake of infiltrated air. High negative pressures in the ejector housing (see Fig. 5) may be created if the system is not operated with a constant load (conveying rate), and allows for partial loads. Fig. 5 shows the influence of feed rate of material conveyed on the pressure at the start of the conveying line and the pressure in the housing (without check valve) by way of example of dolomite. The rate of material conveyed is 400 kg/h. It can be seen that the pressure in the housing is still below ambient pressure at this rate.

In the worst case the material (e.g. from a dosing screw) may be sucked in. In order to avoid this problem; a check valve guarantees infiltrated air intake and the negative pressure is kept at a defined level.

Even if the ejector is "correctly" dimensioned, i.e. is still able to intake a small quantity of gas under full load, mass flow fluctuations may still result given, for example, materials with poor flow properties. This is expressed in a brief "hiccup" of the ejector, i.e. in order to be able to transport more solid matter, a part of the gas is blown backwards. Positive pressure is built up for a short time in the housing instead of a negative pressure.

This is also why it is absolutely essential for a check valve to be integrated into the system which enables infiltrated air intake whilst outwardly sealing the system if there is a positive pressure.

The check valve is to be selected in accordance with the state of the art to ensure that there is no rattling during conveying. The admissible negative pressure will depend on the ejector design (guideline value: approximately 5 – 25 mbars).

3.4 Buffer Volume (Housing)

It is also important to have a small buffer volume in the form of a buffer tank (hopper) using which irregularities in the material feed, slip or unavoidable fluctuations can be buffered.

If, for example, a rotary valve is located too near (without buffer tank) to the ejector, the material in the ejector feed may compress and the system will come to a standstill. As a guide when dimensioning the tank it should be borne in mind that it should at least be possible to store the material collecting during a period of 90 – 120 seconds. The buffer volume may also be used to check (calibrate) the dosing unit (via the front panel).

3.5 Exchangeable Diffusor/ Mixing Pipe

In the case of some materials (e.g. quartz sand or fly ash), wear and/or caking may occur in the diffusor or mixing pipe. For this reason, the entire unit, i.e. capture nozzle, mixing pipe and diffusor should be replaceable.

If a marked drop in conveying performance is noticed, the entire part can be replaced simply. Should the appropriate spare part not be available, an improvement in conveying performance can be achieved by turning the ejector through 180°, thus extending the useful life or bridging the waiting time until a complete spare part is supplied.

3.6 Fluidizing Bottom

In the case of fine materials it may be a good idea to fluidize the material over the bottom of the housing. This will ensure a better flow of the material to the ejector inlet. The bottom is easy to dismantle (flap down) to facilitate easy cleaning and emptying.

4. Incorporating the Ejector into the Pneumatic Conveying System

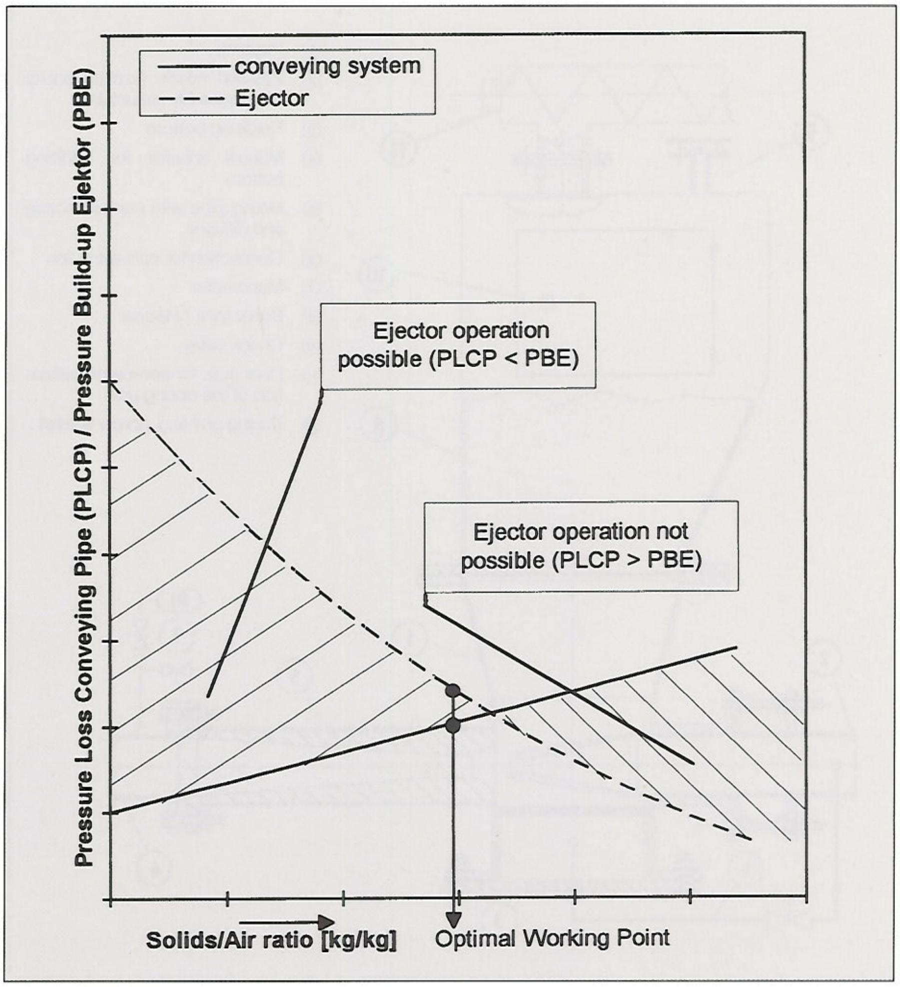
In order to design and adjust the ejector correctly, the pressure loss in the conveying line or the counterpressure generally to be expected at the ejector outlet must be ascertained. The ejector can then be calculated accordingly. An ejector is generally designed by varying the momentum and energy balance; variations can be made by emphasizing or ignoring specific physical processes such as influences on material acceleration, actual frictional losses through solids etc.

The calculation and design of ejectors according to the state-of-the-art will form the subject of a separate piece of work. This is why only brief reference has been made to the most important components such as injection nozzle and mixing pipe/diffusor. Emphasis is placed here on practical applications and the avoidance of installation and planning errors.

In view of their high volume flow and pressure characteristics, the cost favourable Roots blowers are the preferred suppliers of air for ejector conveying. This also means, however, that a maximum supply pressure of the ejector of 900 – 1,000 mbars may not be exceeded under any circumstances.

Fig. 6 shows the characteristic curve for the ejector and the corresponding pneumatic conveying line as a function of the solids ratio. The pressure built up by the ejector must be at least as high as the pressure loss in the conveying line. The build-up of pressure in the ejector will drop quicker than the pressure loss in the conveying line increases, given increasing solids loading. An optimum working point (left from the intersection of the characteristics) can thus be determined, as shown in the figure. It is possible to feed the material via the ejector left of the intersection since a negative pressure is created at all times at the feed point. To the right of the intersection the pressure loss in the conveying line is greater than the pressure build-up via the ejector. It may be possible to infeed the material through the ejector under some circum-

Fig. 6: Working diagram for ejector conveying



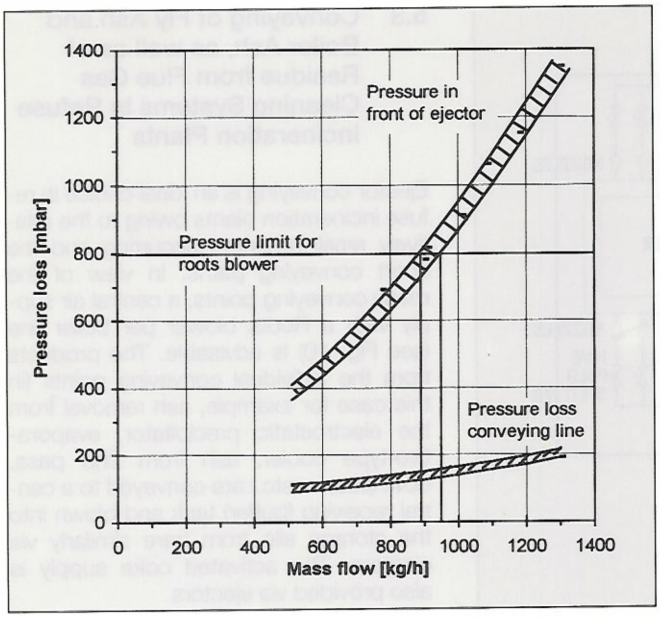


Fig. 7: Interdependence of ejector pressure requirement and conveying rate assuming constant gas quantity

	Limestone $CaCO_3$	Slaked lime $Ca(OH)_2$	Dolomite $CaMg(CO_3)_2$	Magnesium oxide MgO
Mean particle size dp_{50} [mm]	0.01-0.02	0.0025-0.004	0.015-0.025	0.02-0.03
Specific density [kg/m3]	2700	2300	2900	3500
Bulk density [kg/m^3]	800-1200	300-500	950-1300	60-80
Angle of repose [°]	30-45	40-55	35-45	45-60
Particle hardness [Mohs]	2-4	1.5-3	2-4	1-2
Specific surface BET [m^2/g]	0.8-5	20-45	0.5-2	
Geldart-classification [1/1]	A/C	C	A/C	C

Table 1: Physical properties of bulk solids

stances but a positive pressure will prevail at the feed point (see also Fig. 5) and the desirable effect of the ejector will not be achieved.

Since loading has a great influence on the necessary ejector supply pressure, particular care should be exercised here. In the large majority of cases, the ejectors are to be viewed as so-called intermediate pressure ejectors. According to [2], these are characterised by a pressure ratio P_{supply}/P_{system} of between 1.2 and 3. The ejector supply pressure can thus fluctuate between 1.2 and 3 bars in absolute terms depending on ambient pressure. Given greater or smaller pressure ratios reference is made to high or low pressure ejectors respectively.

Fig. 7 uses the example of ash conveying to show the decisive importance of loading on the necessary ejector supply pressure. It can be seen that the critical point is very quickly reached given constant air volume flow and increasing load. The maximum supply pressure was restricted to approximately 800 mbars (gauge) in existing Roots blowers, thus limiting the maximum conveying rate to approximately 900 kg/h.

Since, as already mentioned, ejectors have a very high energy requirement for the inward transfer process, the maximum pressure should naturally be used to best advantage. Otherwise, the investment costs for pipelines, air generation and top hopper filter will rise proportionately to air volume flow.

The selection of transport velocity will depend on the material and the Froude number of the pipeline. Speeds (in particular in smaller lines) of approximately 16 – 20 m/s will be completely adequate for fine-particled solids. The majority of other conveying systems (including pressurised vessel conveying systems!) also operate with line exit velocities in this magnitude, thus defeating the widespread prejudice against ejector conveying that it causes greater pipe wear.

5. Examples of Plants in Use

5.1 Conveying of MgO Ash from the Electrostatic Precipitator of a Waste-Liquor Burning Plant

In this particular case fly ash is conveyed from a sulphite liquor-fired boiler. A rotary lock was originally built into the system which was intended to convey the light MgO ash (for material data see Table 1) from the electrostatic precipitator to a storage hopper for subsequent wet scrubbing. A maximum of 2.6 t/h of MgO ash are conveyed (this corresponds to an ash volume flow of approximately 30 – 40 m^3/h).

The difficulties with the rotary lock resulting from leakage air were so great that the conveying system was brought to a complete standstill and the electrostatic precipitator hoppers were entirely filled with ash. The entire system then had to be shut down via short-circuiting in the electrostatic precipitator. Finally the MgO ash (approximately 100 m^3) then had to be drawn off via a suction vehicle.

The constant faults, which also reoccurred shortly after new rotary valves had been fitted, compelled the plant operator to keep such suction vehicles in reserve on a continuous basis and to clean the filter area regularly. The ash, a valuable raw material, taken off in this way was more or less stored in the open air; its small particle size and low material weight meant that it blew away, thus representing a constant burden to the environment and the immediate vicinity.

For this reason, the old ash conveying system was replaced by an ejector conveying system during normal boiler operation and has now been running around the clock virtually fault-free for some 5 years now (with the exception of an annual replacement of the diffusor unit).

5.2 Conveying and Injection of Slaked Lime to Reduce Pollutants in Flue Gases from Firing and Drying Systems

The use of ejectors is always expedient when a low solids ratio is necessary for technical reasons. An example of this is a plant for the desulphurisation of coal-fired power stations by direct desulphurisation. Fig. 8 shows the basic design of such a plant for the injection of slaked lime into combustion chambers or exhaust gas ducts. Reference is made to [5], for example, which provide more details on this subject.

The material ($Ca(OH)_2$ in this particular case) is drawn off from a storage silo and metered by means of a vibrating bottom and screw feeders. The metered quantity drops to an ejector which blows the material into a combustion chamber or an exhaust gas duct via a multiple distributor.

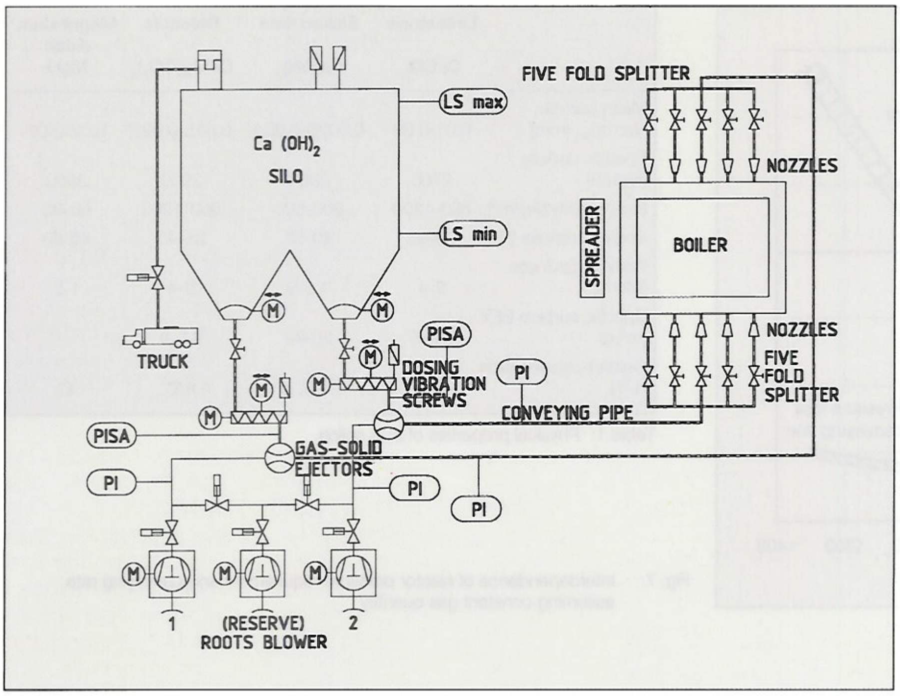


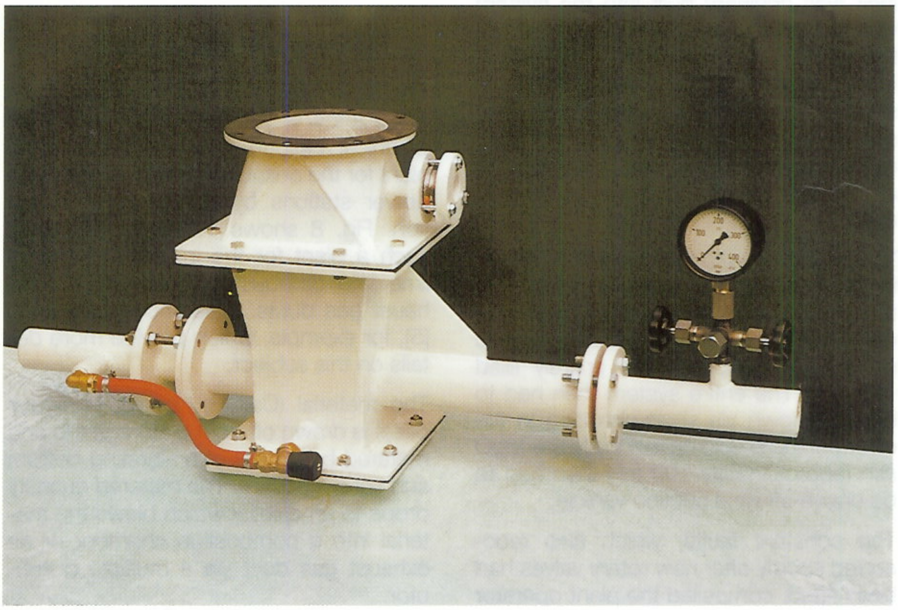
Fig. 8: Direct desulphurisation plant

It is generally known that in the ejector conveying of Ca(OH)$_2$, diffusors made of steel, steel alloys and plastics in general will be completely clogged after approximately 1 – 2 days. It will then be completely impossible to continue conveying operations. The caking will harden completely and will then be difficult to remove mechanically.

This strange behaviour at air velocities of around 20 m/s has led to manufacturers of such plants making the lines of rubber and not steel. This has not, however, been able to solve the problem in the ejector itself.

Specials plastics are used which, firstly, prevent caking and are, secondly, so wear-resistant that a service life of up to 6,000 operating hours is achieved. This means that the advantages of ejector conveying can also be used for this particular case of application. Fig. 9 shows such a special ejector for conveying caking materials.

Fig. 9: Ejector for conveying caking materials



5.3 Conveying of Fly Ash and Boiler Ash, as well as of Residue from Flue Gas Cleaning Systems in Refuse Incineration Plants

Ejector conveying is an ideal choice in refuse incineration plants owing to the relatively small amounts occurring and the short conveying paths. In view of the many conveying points, a central air supply with a Roots blower per boiler line (see Fig. 10) is advisable. The products from the individual conveying points (in this case for example, ash removal from the electrostatic precipitator, evaporative-type cooler, ash from 2nd pass, downpasses etc.) are conveyed to a central receiving (buffer) tank and blown into the storage silo from here similarly via ejectors. The activated coke supply is also provided via ejectors.

Owing to the mode of plant operation and the resultant ash consistency, even low moisture content in the conveying air may lead to clumping and caking so that only dried air should be used. Furthermore, temperatures should not be allowed to fall below a range of 80 – 100 °C either in the conveying lines or in the intermediate equipment. The air is therefore to be kept hot where at all possible and the conveying lines to be sufficiently insulated.

In refuse incineration plants this applies in particular to ash from so-called spray dryers whose CaCl$_2$ crystals react with the smallest moisture content in air or flue gas, causing the crystals to melt. This leads to uncontrollable caking and clumping. The individual ejector conveying lines must be calculated exactly and the entire air flow precisely divided up over individual lines.

6. Special Ejector Design for Fine-Particled Materials

6.1 Ejectors with Several Injection Nozzles

A marked improvement in efficiency is to be observed in single-phase air-air ejectors [2] if the incoming air jet is divided equally over several orifices. The same results have been determined experimentally for two-phase mixtures (airwater) in the ventilation of clarifying basins. Corresponding investigations into solids ejectors are still to be made.

6.2 Coanda Ejectors

The carrier air of an ejector cannot not only be introduced centrally but also via a concentric annular clearance. This may

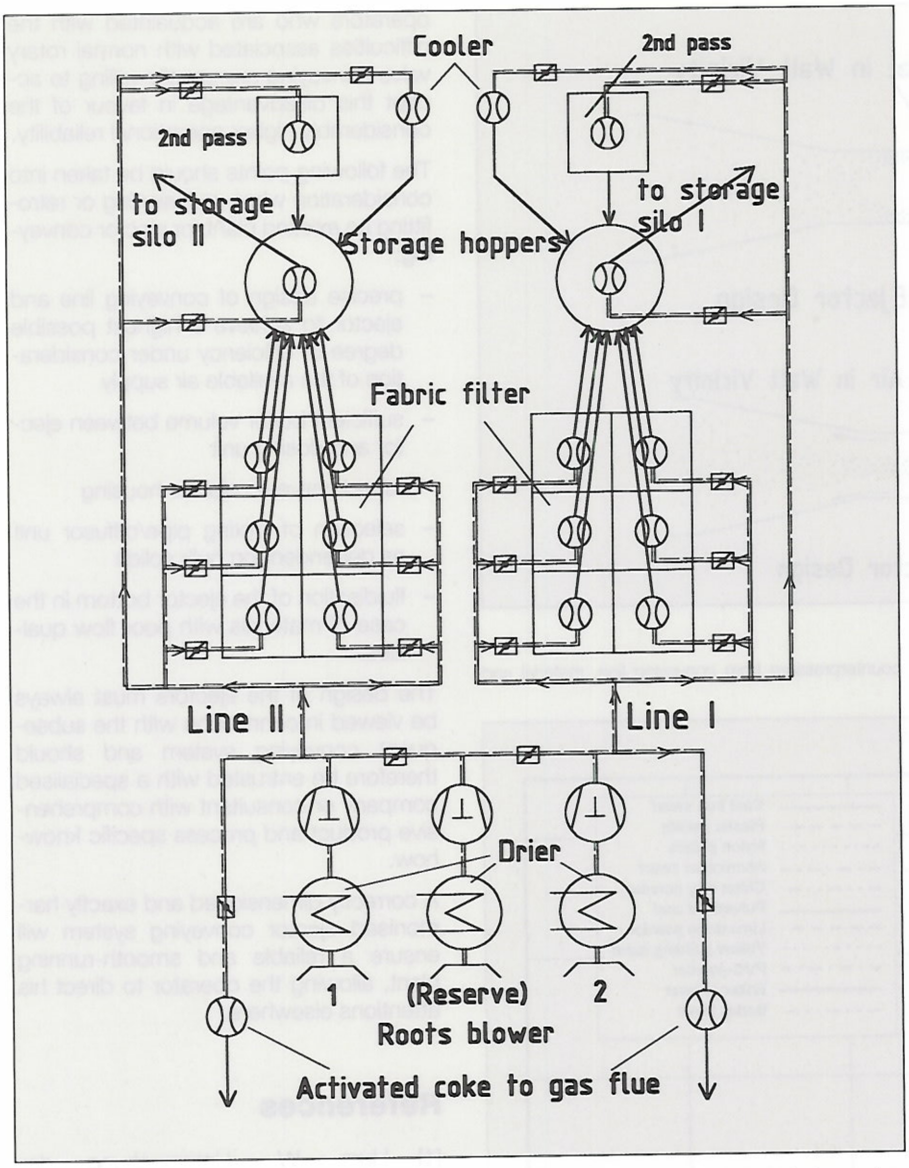


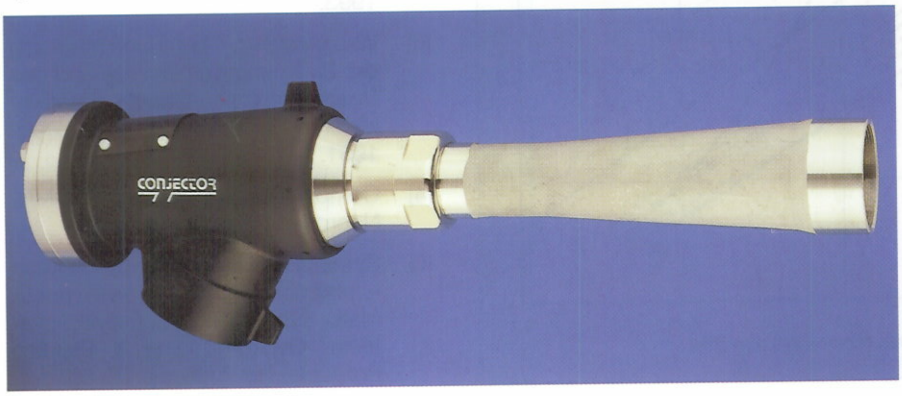
Fig. 10: Pneumatic conveying of fly-ash and activated coke with ejectors and central air supply for a refuse incineration plant

have a variety of advantages depending on the individual case.

Fig. 11 shows a so-called Conjector [4] with an annular clearance nozzle. The carrier air is introduced via a concentric clearance.

The conjector uses the so-called Coanda effect to generate the carrier jet. An trip ledge serves to ensure that the gas flow runs along the adjacent sheath surface of the inner side.

Fig. 11: Conjector



Contrary to conventional ejectors, a part of the solids is not pressed against the housing wall as a result of the expanding carrier jet, but can distribute evenly over the cross-section (see Fig. 12).

This may lead to fewer problems with caking on the walls of the diffusor and mixing pipe, as has essentially been confirmed in tests. Despite the normal steel version, this ejector type led to a considerable reduction in caking in the mixing pipe/diffusor area.

However, the performance range was limited somewhat since the material feed of the horizontal ejector did not function optimally. The correct alternative would have been a central feed of the material via a fluid bottom. Another advantage of the conjectors is also the simple adjustment of performance by adjusting the width of clearance. This means that increasing the supply pressure for higher performance presents no problem. On the other hand, the power consumption of the compressor in the case of partial loads may lead to a reduction in operating costs by reducing the supply pressure (clearance width greater).

Fig. 13 shows the performance of conjectors of different nominal widths (DN50-DN100) as dependent on end pressure in the conveying line. A variety of materials of different particle size and density are shown. These characteristics also apply in principle to ejectors with a central injection nozzle.

7. Concluding Remarks

Ejectors have been used for some time now to inwardly transfer solids into pneumatic conveying lines. The main advantages of ejectors are listed below.

- slight negative pressure at the feed point, thus eliminating problems associated with leakage air, such as when conveying by rotary valve alone
- simple design and no moving parts, i.e. low in maintenance
- suitable for high temperatures
- continuous mode of operation
- high operational reliability
- long useful life (up to 20,000 operating hours for one diffusor unit, depending on wall and bulk solids pairing)
- material flow enhanced by infiltrated air intake via check valve.

The great disadvantage of ejector conveying is the high energy consumption for the inward transfer process. However,

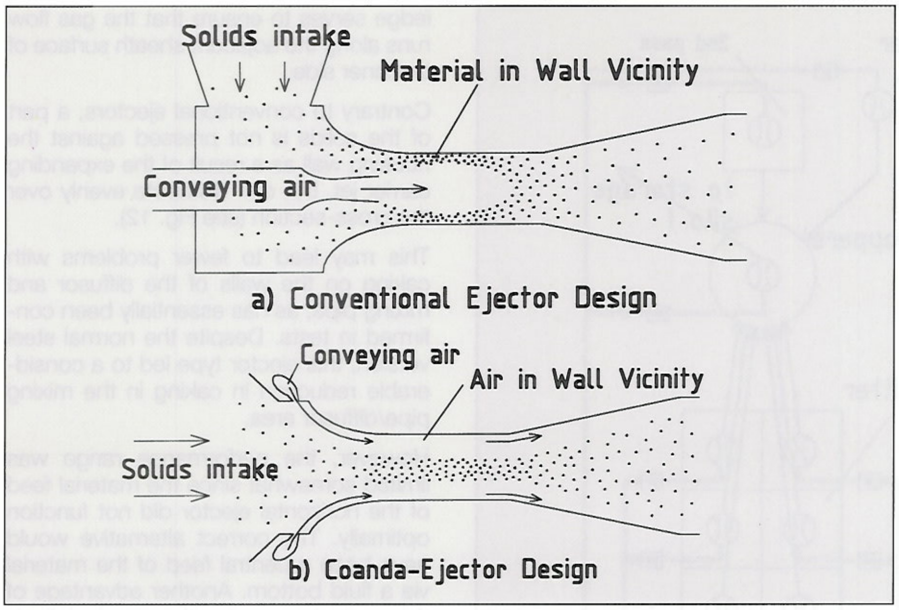
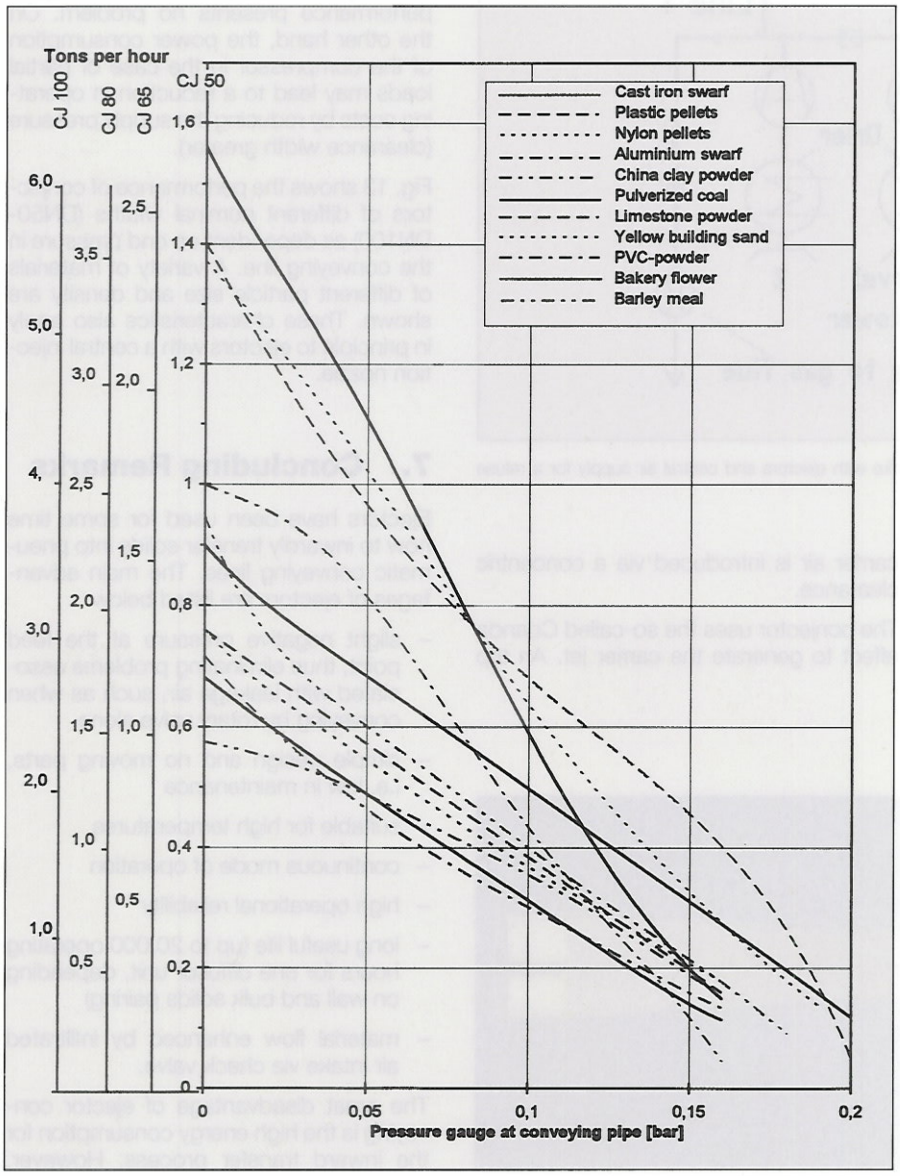


Fig. 12: Solids flow for different ejector designs

Fig. 13: Ejector-performance (Conjector) dependent on counterpressure from conveying line, material and nominal width



operators who are acquainted with the difficulties associated with normal rotary valve conveying are usually willing to accept this disadvantage in favour of the considerably higher operational reliability.

The following points should be taken into consideration when redesigning or retrofitting an existing plant for ejector conveying:

- precise design of conveying line and ejector to achieve a highest possible degree of efficiency under consideration of the available air supply
- sufficient buffer volume between ejector and dosing unit
- check valve on ejector housing
- selection of mixing pipe/diffusor unit as dependent on bulk solids
- fluidisation of the ejector bottom in the case of materials with poor flow qualities.

The design of the ejectors must always be viewed in connection with the subsequent conveying system and should therefore be entrusted with a specialised company or consultant with comprehensive product and process specific knowhow.

A correctly dimensioned and exactly harmonised ejector conveying system will ensure a reliable and smooth-running plant, allowing the operator to direct his attentions elsewhere.

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