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Decrease in Consumption of Compressed Air in Dry Ice Blasting Machine

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Dry ice blasting is a highly efficient and environmental friendly method for elimination of undesired layers from various materials. Dry ice blasting is used especially in cleaning of industrial manufacturing moulds, welding robots, and many other industrial applications where water cleaning cannot be used and/or savings of detergents are required. HVAC systems are currently very promising area of application. In contrast with mechanical cleaning, dry ice blasting technology requires a source of compressed air which supplies kinetic energy to pellets of dry ice. Kinetic energy of air-pellets mixture is a key factor influencing the efficiency of the cleaning process. Production of sufficient amount of compressed air with desired properties (0.6 MPa, 5 Nm^3/min) is, however, a highly energy intensive process and rather expensive, too. Central distribution of compressed air with these properties is commonly not available in industrial facilities.

This paper presents an innovation of blasting machine with dry ice shaving mechanism that has not yet been published. Development phase focused on decrease of compressed air consumption which is used to power dry ice shaving mechanism. This consumption at current blasting machines may reach up to 25 % of total compressed air consumption. Standard pneumatic drive of the shaving mechanism was innovatively replaced with electric drive. This new arrangement allows for significant reduction in consumption of compressed air, as proved by our measurements. Considerable increase in total performance of the blasting machine and operation productivity is the main benefit of the new innovation. This may also be applied in facilities where insufficient flow of compressed air had prevented its application.

Successful experimental measurements in a research facility were followed by recommendations of testing the innovated machine in industrial scale. Our experience proves that the innovation has a great potential in industry. Widespread use is, however, conditioned by user-friendly handling and control system. The control system is the subject of the last chapter of this paper.

1. Introduction

Dry ice blasting is a modern surface cleaning technology which originated in 1980s. Over the time, dry ice blasting has surpassed conventional mechanical and chemical based technologies of cleaning. Benefits of dry ice blasting include high speed of the cleaning process and absence of any cleaning residues as all the dry ice sublimates after hitting the surface. Dry ice pellets, flowing in the compressed air, work as a cleaning medium in the dry ice blasting process. Dry ice pellets consist of solid carbon dioxide (CO_2) of -78.5 °C temperature (Figure 1).

The air stream for blasting is usually generated by a pneumatic system with a screw-type compressor. The pellets are accelerated by the compressed air stream coming through a Laval nozzle at a jet pressure of 3 to 12 bar (0.3 - 1.2 MPa) and a maximum volume flow rate of 11 Nm^3/min, depending on the application in question and depart from the nozzle at almost the speed of sound (Spur et al., 1999). Jetting in up-to-date types of nozzles is greater than the speed of sound.

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Figure 1: Fresh dry ice pellets (actual size)

Technology of dry ice blasting is widely applied in automobile, aircraft and railway industries for cleaning of surface from undesired substances (e.g. rust, paints, oils, resins, etc.), and for cleaning of industrial manufacturing moulds, ovens, conveyors, extruders and presses (Stratford, 2000). Pipe cleaning of HVAC systems seems to be a very promising area of dry ice blasting application. More opportunities include surface pre-treatment for coating and joining for improving the adhesive strength (Elbing et al., 2003). Larger blocks of dry ice are used in food industry for food cooling. Dry ice blasting may be considered an environmental friendly technology since the dry ice is a by-product of chemical industry and therefore does not additionally increase CO_2 concentrations in the atmosphere.
Mechanism of undesired particle elimination is based on compressed air drive. Although the mechanism has not been fully discovered and described, its main aspects include (Uhlmann et al., 2009):

- Mechanical effect related to the kinetic energy of the dry ice pellets hitting the surface
- Temperature effect of local cooling causing loss of the surface elasticity and its embrittlement
- Expansion effect related to the sublimation of the dry ice pellets hitting the surface
- Aerodynamic drag separation

Higher jet flow rate causes higher local pressure and thus also causes higher efficiency of the particle removal (this is the basic principle of the technology) (Liu et al., 2011). However, compressed air acceleration is one of the main disadvantages of the dry ice blasting. Blasting itself causes significant noise (100-120 dB) but mostly, compressed air is one of the most expensive commodities used in industry nowadays, which is due to the low efficiency of compressed air production. Saidur et al. (2010) conducted an extensive research and concludes that only 10-20 % of the total input energy is utilized for useful work in the compressed-air system. Major energy loss takes place in the form of waste heat and through the leakage of compressed air. Energy savings concerning the compressed air are therefore a subject of many papers. Dindorf et al. (2012) points out that reducing final pressure of air by 0.1 MPa (1 bar) reduces energy costs by 15 %. Santos et al. (2013) presents the acoustic method for detecting leaks in gas pipelines.

2. Dry ice blasting machine

Dry ice blasting machine is the device that transports dry ice pellets to the surface to be cleaned. The machine (see Figure 2) is a relatively simple piece of equipment into which the dry ice blocks are inserted (250 x 125 x 125 mm). Blocks are then shaped in the machine using a shaving mechanism.

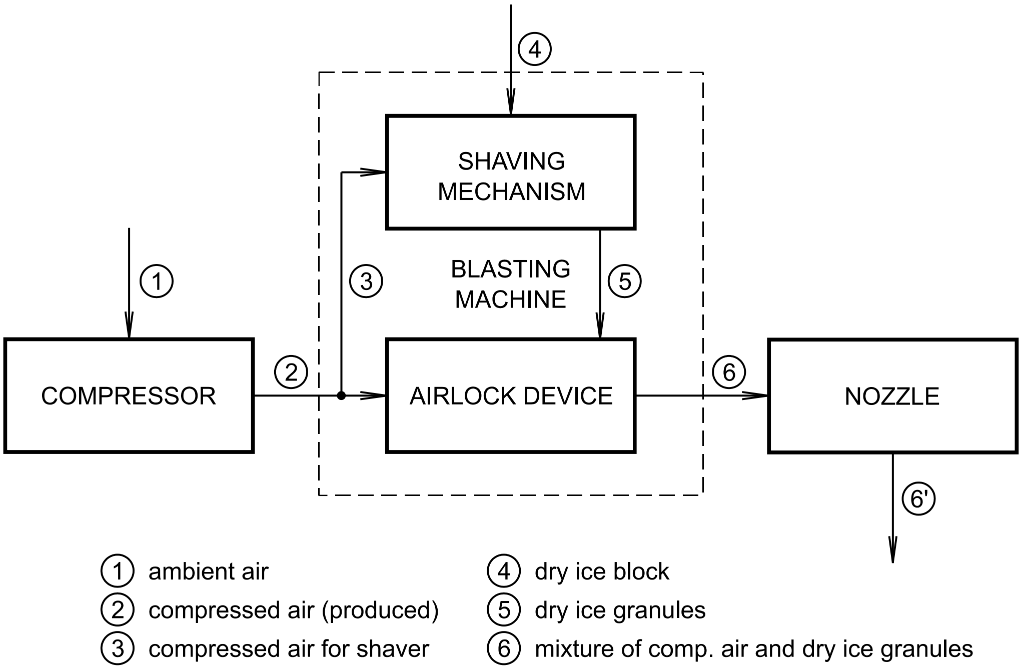

Figure 2: Block scheme of the dry ice blasting machine with compressor

Granules of dry ice are shaved from the dry ice blocks using a rotating knife wheel. Granules size depends on the knife wheel rotations, i.e. on rotations of pneumatic motor which drives the wheel. Shaved dry ice is lead to an airlock device which dispenses the appropriate amount of dry ice through the pressurized hose with Laval nozzle mounted at the end. There is also the so called two-hose system with the pellets/granules being transported in low pressure (to protect the pellets from excessive degradation and sublimation) in one hose to the cleaning nozzle where the pellets are accelerated by an air source from a second hose (Stratford, 2000).

Most of the compressed air serves as a medium for acceleration of dry ice granules. However, significant share of the compressed air is consumed in the shaving mechanism pneumatic motor. The pneumatic drive of the shaving mechanism is a subject of the innovation described below. Blasting machine may directly use dry ice pellets as an alternative. The pellets are supplied into the hopper without any previous shaving. This alternative does not consume compressed air in the shaving mechanism drive but does not allow for any options concerning dry ice granules size. Also, dry ice blocks have longer storage life, compared to dry ice pellets.

Our team consulted the operator of dry ice blasting machine who confirmed that air flow rate of 5 Nm^3/min with 0.5 - 0.6 MPa pressure are the standard operating parameters which were also used in measurements described below.

3. Measurement of shaving mechanism drive consumption

Shaving mechanism consumption was measured using orifice plate with corner taps. Difference between static pressures of the compressed air before and beyond the orifice was identified by a differential pressure sensor located below the orifice. Measurement set further included sensors for absolute pressure and resistance thermometer (see Figure 3). Measurement set was connected before the shaving mechanism and into the air allocated for the shaving mechanism drive. Volume flow rate (see Table 1) corresponds to the compressed air consumption allocated for the shaving mechanism.

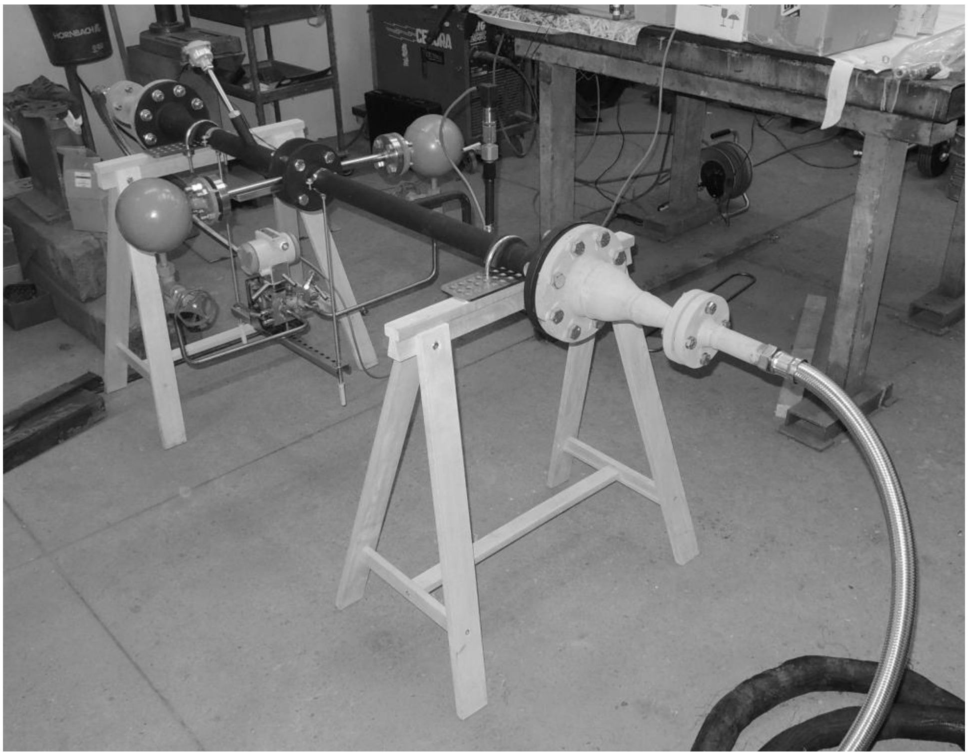

Figure 3: Measurement set for assessment of compressed air consumption (orifice plate with corner taps)

Flow rate and streaming velocity was calculated using the Eq (1) and Eq (2).

$$Q_V = \frac{C}{\sqrt{1\text{-}\beta^4}}\ \varepsilon\ \frac{\pi}{4}\ d^2 \sqrt{\frac{2\Delta p}{\rho}} \tag{1}$$

$$v = \frac{4\ Q_V}{\pi\ D^2} \tag{2}$$

where Q_V is volume flow rate (m^3/s), C is orifice coefficient (-), β is diameter ratio (-), ε is expansion factor (-), d is orifice diameter (m), Δp is differential pressure (Pa), ρ is fluid density (kg/m^3), v is velocity over the orifice (m/s) and D is pipe diameter (m).

Average air consumed by the shaving mechanism equals to 57.70 ± 0.17 Nm^3/h. This consumption amounts for ca. 19 % of the total consumption of the dry ice blasting machine (300 Nm^3/h).

Table 1: Results of repeated measurements of shaving mechanism pneumatic drive consumption

Parameter	*Value (unit)*	*Parameter*	*Value (unit)*
Measurement time	1,200 s	Average velocity (v)	2.38 m/s
Average temperature	14.0 °C	Average volume flow rate (Q_V)	57.70 Nm^3/h
Average absolute pressure	0.570 MPa	Standard deviation	0.17 Nm^3/h

4. Substitution of pneumatic drive with electric drive

Basic parameters for substitution of the existing shaving mechanism pneumatic drive were its performance and rotations. Asynchronous three-phase electric motor with 0.55 kW at 50 Hz frequency was selected as the substitution alternative (see Figure 4). Only a minimum power reserve was preserved since efficiency values of motors change with load. Peak efficiency typically appears at 75 to 100 % of the motor load. Lightly loaded motors will experience much lower efficiency values than the nominal nameplate value (Li and Curiac, 2010). In order to control motor rotations (and thus the dry ice granules size, too), frequency converter was integrated into the motor.

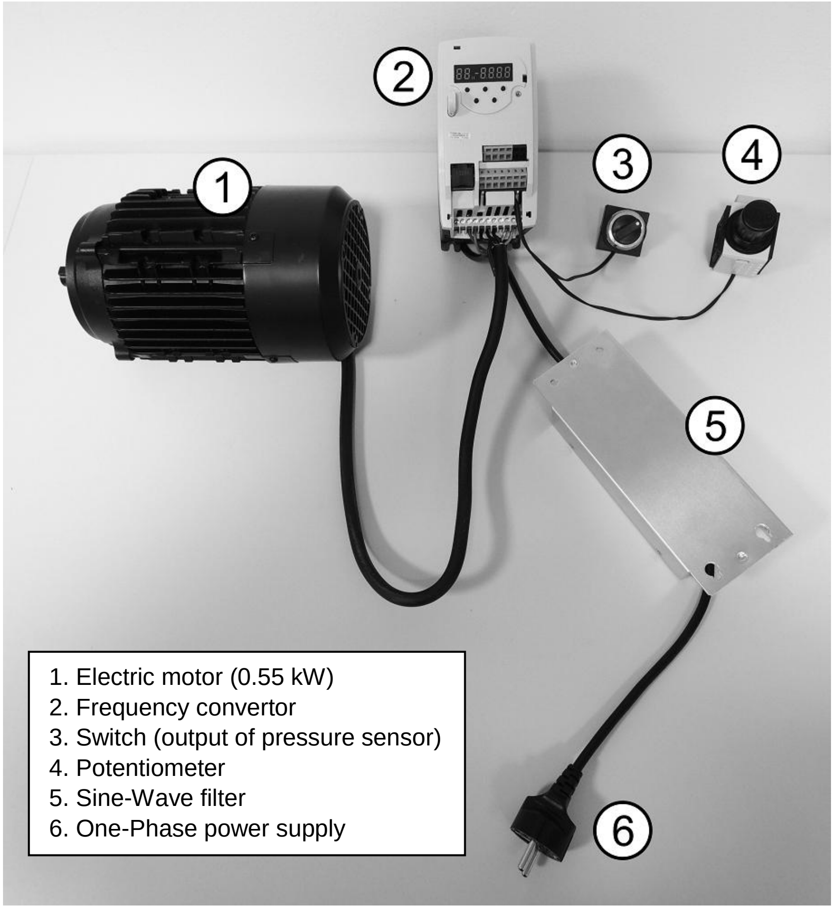

Figure 4: Arrangement of new electric drive of shaving mechanism with control features

Relevant motor with a frequency convertor was installed instead of the pneumatic motor, and was tested in laboratory. The motor proved its suitability as a shaving mechanism drive. In terms of serviceability, properties of the new electric motor and the original pneumatic motor do not significantly differ. Operator of the dry ice blasting machine now only has to ensure stable power supply during the blasting. It should not be difficult with the one-phase power supply of the motor with frequency convertor.
The power consumption of compressor in kW to the volume in cubic meter of air delivered at ambient conditions (m^3) is determined as specific energy consumption (SEC) in kWh/m^3.

$$\mathrm{SEC}= \frac{P_A}{q_{FAD}} \tag{3}$$

where P_A is average power draw (kW) and q_{FAD} is free air delivery (m^3/h).
Common SEC at 0.7 MPa pressure equals to 0.11-0.13 kWh/m^3 (Dindorf et al., 2012). Calculations work with the value 0.13 kWh/Nm^3 since an older compressor was used and the ambient conditions were close to the normal conditions (0°C and 0.1 MPa) during the measurement. Consumption of electrical energy in the compressor for pneumatic drive of the shaving mechanism thus equals to 7.5 kWh/h of operation. New electric motor consumes 0.55 kWh/h of operation. 6.95 kWh was saved and electrical energy consumption of the process was reduced by 17.8 %.
Machine operator required that the existing control features of the shaving mechanism start-up and of granules size adjustment do not change. Pneumatic motor used to start with a pneumatic valve. Pneumatic valve was substituted with pressure sensor which switches relevant contacts of the frequency convertor. Pneumatic regulator securing control of the pneumatic motor rotations was substituted with potentiometer. The potentiometer is connected to the frequency convertor, and allows selecting a particular dry ice granules size. This solution is fully compatible with the previous operating procedures, and operator does not face any difficulties.

5. Conclusion

Dry ice blasting is a highly energy intensive process with high requirements for compressed air supply. Every reduction in compressed air consumption creates distinctive savings of electrical energy. Dry ice blasting machine, presented in this paper, was innovated using substitution of dry ice shaving mechanism pneumatic drive with electrical drive. Tests proved that consumption of compressed air was reduced by 19 % (for working pressure of 0.57 MPa). Considering the consumption of the new electric motor, electrical energy savings correspond to 17.8 %. We may conclude that the substitution is a valuable savings measure with a very promising payback period and a great application potential. Major benefit of the innovation is the reduction of energy intensity of the technology. Also, the innovation is a great contribution in all facilities where the insufficient flow rate of the compressed air may prevent application of the dry ice blasting technology (or where a more powerful compressor would have to be leased instead).

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