Optimization of a compressed gaseous CO2 energy recovery dry ice pelletizer

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ABSTRACT

The disadvantages of the existing dry ice electromechanical pelletizers have been revealed. A schematic flow diagram of the new dry ice energy recovery pelletizer and a carbon dioxide TS diagram with the processes of the new pelletizer have been presented. The functions of the diameter of the piston expander of the new dry ice pelletizer and dry ice pressing pressure depending on the pressure of compressed gaseous CO2 have been derived. The optimal diameters of a piston expander for the dry ice pelletizer have been determined.

Keywords: granulating, carbon dioxide, dry ice, piston expander, recovery.

INTRODUCTION

As is known, dry ice goes from a solid aggregate state to a gaseous state without a liquid phase at a temperature of 194.65 K (-78.5 °C) under atmospheric conditions. Due to these properties, dry ice is widely used as cleaning material in cryogenic blasting and as cooling material for temperature-controlled carriage and other applications [1, 2]. The global dry ice sales market is predicted to grow at CAGR equal to 6.8% over the next 10 years. The dry ice market is constantly developing in the field of manufacturing dry ice making machines (hereinafter referred to as pelletizers) [3]. The first patented dry ice granulating technology, on the basis of which all pelletizers in the world are now manufactured, was invented in 1928 [4] and was based on the use of electromechanical pressing ice energy, and has not changed conceptually since then. But even now, after the industrial and digital revolutions, pelletizers consume a lot of energy, have a significant weight and dimensions, they are difficult to manufacture and they have a relatively low failure tolerance, which altogether leads to an increase in the total ownership cost of a pelletizer.

The new pelletizer invented by IRBISTECH LLC in 2015 [5] is made partly by analogy with the existing pelletizers, but it recovers energy.

The novelty lies in the transformation of compressed gaseous CO2, which is obtained after liquid CO2 expansion in a gas piston expander in mechanical force for press

the solid carbon dioxide particles formed also during liquid CO2 expansion. Thus, no external source of electromechanical energy is required.

Being capable of utilizing compressed gaseous CO2 energy, the new pelletizer is predicted to have the following advantages over the world analogues with the equal performance: the power consumption is up to 70-90 times lower; the failure tolerance is up to 10 times higher; the weight is 3-4 times lower; lack of hydraulic oil and possible leakage thereof. One of the main issues in the development of the new pelletizer is to determine the optimal dry ice pressing pressure in conjunction with the optimal diameter of a piston expander.

PRIMARY PARTITION

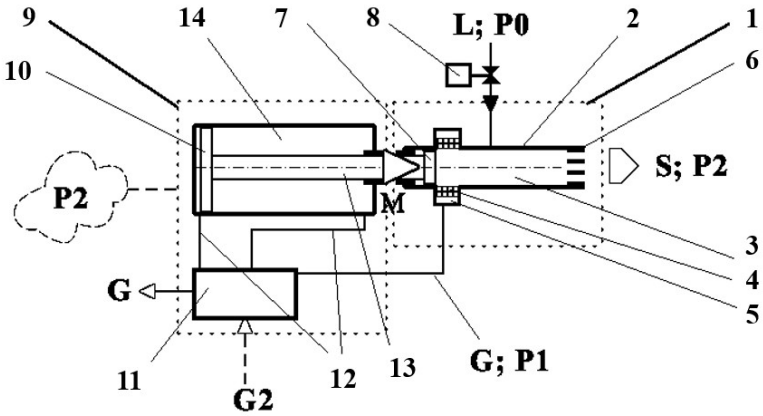

Figure 1. Basic technological scheme of a single linear gas piston expander appliance [5].

Figure 1 shows a schematic flow diagram of a single linear gas piston expander appliance. The device has one piston-type compression unit 1 and power unit 9 based on gas piston expander 14. Compaction unit 1 includes housing 2 with cylindric inner chamber 3, shutter 6 attached to housing 2 at one end and pressing plunger 7 disposed inside chamber 3 bounds chamber 2 at the other end, filter element 4 mounted into housing 2 connects the inner cavity of chamber 3 to collecting device 5. Valve 8 is designed to supply liquid carbon dioxide to chamber 3. Power unit 9 has gas piston expander 14 operating via gaseous carbon dioxide (G), the flow of which is controlled by control unit 11. Gaseous carbon dioxide (G) is supplied to expander 14 and is released therefrom through gas connections 12. Control unit 11 is supplied with carbon dioxide gas (G) by carbon dioxide gas (G) leaking from compaction unit 1 through collecting device 5. Pressing unit 1 and expander 14 are structurally designed so that they are able to hold the intermediate pressure (P1) of gaseous carbon dioxide (G) within themselves. Control unit 11 has a PLC system, a gas valve control system and a gas buffer for the intermediate storage of gaseous carbon dioxide (G). Inner displaceable piston 10 disposed within

expander 14 hermetically divides the inner cavity of expander 14 into two parts, the volume of which can vary depending on the disposition of inner movable piston 10. The linear force is transferred from power unit 9 to pressing unit 1 by filling that part of the cavity of expander 14 with gaseous carbon dioxide (G), which is disposed on the other side of the compaction unit relative to internal movable piston 10. The intermediate pressure (P1) of the gaseous carbon dioxide (G) acts on the surface of inner movable piston 10 and thus creates a force transmitted through rod 13 to plunger 7. When plunger 7 reaches approximately the middle of the pressing chamber, shutter 6 opens and the pellet leaves the pressing chamber and the plunger begins to go back.

The device is capable of producing compacted solid carbon dioxide (S) only discretely, since it takes time for plunger 7 to go back to the reverse position to fill chamber 3 with solid carbon dioxide particles.

It is obvious from Figure 1 that the higher the diameter of piston 10 and the pressure of gaseous CO2, the higher the pressing force on plunger 7, but therewith there is a limit for the produced gaseous carbon dioxide in pressing chamber 3 as the volume of chamber 3 is just the thing that defines the weight of the produced gas. Thus, there is a physical relationship between the diameter of piston 10, the diameter of chamber 3, the pressure of gaseous CO2 and the pressing force of dry ice, which must be revealed to develop the optimal design of a pelletizer.

Producing pellets from solid carbon dioxide (S) particles which is traditionally used in industry is characterized by the following parameters and their values:

- **The storage pressure of liquid carbon dioxide** (L) in thermally insulated tanks is 265-300 psi [6], which is 1.6-2.07 MPa;
- **The coefficient of conversion of liquid carbon dioxide** (L) to solid carbon dioxide (S) after throttling liquid carbon dioxide (L) to atmospheric pressure is 0.45-0.5 [7] by weight.
- **The pressure of the emitted gaseous carbon dioxide** (G) at the outlet of the device is approximately equal to atmospheric pressure [8];

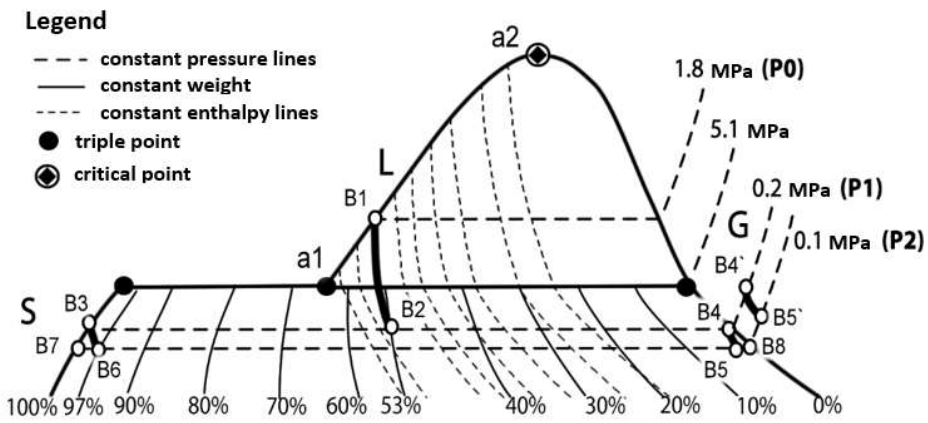

Figure 2. TS diagram and the corresponding processes of an energy recovery-based method for producing granulated solid carbon dioxide (S) [7].

Figure 2 shows a TS diagram and the corresponding processes of an energy recovery-based method for producing granulated solid carbon dioxide (S). Point B1 located on saturation line a1-a2 characterizes the state of carbon dioxide in a liquid aggregate state (L) when stored in a tank at a pressure of, for example, 1.8 MPa. Line B1-B2 characterizes throttling liquid carbon dioxide (L) from point B1 to point B2, which describes the conversion of liquid carbon dioxide (L) into compressed gaseous carbon dioxide (G) and solid carbon dioxide (S) particles.

Point B2 shows the thermodynamic equilibrium of a solid carbon dioxide (S) mixture at a pressure of 0.2 MPa (point B3) and gaseous carbon dioxide at a pressure of 0.2 MPa (point B4), on the basis thereof, it is possible to calculate the proportion of the resulting solid carbon dioxide, which is equal to the result of dividing the length of segment B2-B4` by the length of segment B3-B4 and is approximately 0.53 (53%), which is close to the above-mentioned values.

The data on the density of carbon dioxide on the gas-solid saturation line were collected from four different graphs.

Saturated CO2 vapor pressure		Data from source 1 [9]		Data from source 2 [10]		Data from source 3 [11]		Data from source 4 [12]		Arithmetic mean of density
atm	psi	ft3/lb	kg / m3	ft3/lb	kg / m3	dm3 / kg	kg / m3	dm3 / kg	kg / m3	kg / m3
1	14.7	6	**2.7**	6	**2.7**	430	**2.3**	390	**2.6**	**2.56**
2	29.4	3.1	**5.2**	3.5	**4.6**	190	**5.3**	200	**5.0**	**5.00**
3	44.1	2	**8.0**	2	**8.0**	130	**7.7**	150	**6.7**	**7.59**
4	58.8	1.4	**11.4**	1.5	**10.7**	95	**10.5**	100	**10.0**	**10.66**
5	73.5	1.2	**13.3**	1.1	**14.5**	75	**13.3**	76	**13.2**	**13.59**

Table 1. Density of the compressed gaseous carbon dioxide on the solid phase-gas saturation line depending on the pressure of the compressed gaseous carbon dioxide according to different sources.

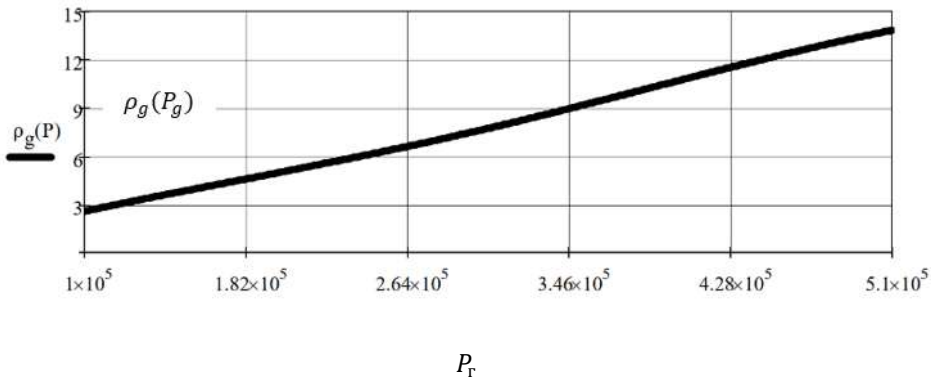

Figure 3. Data interpolation graph according to Table 1.

Any optimization problem must have such parameters and their restrictions as:

1. The pressure of the gaseous carbon dioxide (P_g) formed directly after throttling liquid CO2;
2. The pressing pressure (P_{press}) of solid carbon dioxide as a quality indicator of the produced granules (products);
3. The diameter of the piston expander (D_p) that affects the manufacturing technology, dimensions and cost of equipment.

Restrictions:

1. The pressure of carbon dioxide gas can range from 0.1 MPa (atmosphere) to 5.2 MPa (a CO2 triple point);
2. The pressing pressure of solid carbon dioxide should be within the range from 150 atm (cooling pellets) [11] to 220 atm (cryogenic blasting pellets) [14];
3. The diameter of the piston expander must be within the dimensional range of the diameters of the pneumatic cylinders produced according to an ISO 15552 international standard: 160, 200, 250 and 320 mm.

The packing density of the particles in the chamber of the compaction unit after liquid carbon dioxide expands, the values of which are within the range of 521-850 kg / m^3 [15]. To solve the optimization problem, a value of ρ_s =720 kg/m^3 was taken, which corresponds to the experimental data of IRBISTECH LLC.

Volume equality equation for the produced compressed gaseous CO2 and the volume of the cavity of the piston expander for 50% of the piston stroke (self-compacted CO2 snow must be compressed approximately 2 times to achieve a theoretical density of dry ice of 1400-1600 kg / m^3 [16]):

$$\frac{m_g}{\rho_g(P_g)} = \frac{\pi {D_p}^2}{4}\frac{L_p}{2} \qquad \text{Eq (1)}$$

Where m_g is the weight of the gaseous CO2 produced per cycle, kg, P_g is the weight of the gaseous CO2 produced per cycle, Pa, $\rho_g(P_g)$ is the function of density of the saturated CO2 vapors on the saturation line in Figure 3, kg / m^3, D_p is the diameter of the expander piston, m, L_p is the stroke length of the expander, m.

Since the conversion factor is approximately 0.5 [17,18], let us take the equal portions of the formed CO2 snow (m_s) and compressed gaseous CO2 (m_r) at throttling, then:

$$m_g \approx m_s = \rho_s \frac{\pi {d_c}^2}{4} L_c \qquad \text{Eq (2)}$$

where d_c is the diameter of the pressing chamber, m, L_c is the length of the pressing chamber, m, ρ_s is the density of self-compacted CO2 snow in the pressing chamber, kg / m^3.

Substituting equation 2 into equation 1 we obtain:

$$\frac{\rho_s \frac{\pi {d_c}^2}{4} L_c}{\rho_g(P_g)} = \frac{\pi {D_p}^2}{4}\frac{L_c}{2} \qquad \text{Eq (3)}$$

When deriving the diameter from equation 3 we obtain equation 4 for an optimal diameter for the complete receit of the produced gas by the piston diameter cavity:

$$\boldsymbol{D_p(P_g) = d_c\sqrt{\frac{2\rho_s}{\rho_g(P_g)}}} \qquad \text{Eq (4)}$$

According to Figure 1 let us derive a balancing force equation for piston 10:

$$P_g \frac{\pi D_p (P_g)^2}{4} - F_{fr} - F_{ret} - P_{press}\frac{\pi {D_c}^2}{4} = 0 \qquad \text{Eq (5)}$$

Where F_{fr} is the friction force of the expander piston, F_{ret} is a force that tends to return the piston to its original position, P_{press} is the pressure that acts on the end of the pressing plunger.

The friction force (F_{fr}) in equation 5 is equivalent to 0.03 MPa according to the experimental data of IRBISTECH LLC, i.e. the pressure of the beginning of the piston movement. The return force (F_{ret}) in equation 5 is created by maintaining constant pressure on the other side of the piston, which creates the effect of a "pneumatic spring" with a constant return force in any position of the piston. The

pressure on the other side is 0.14 MPa according to the experiments of IRBISTECH LLC. Substituting these values into equation 5 we obtain:

$$P_g \frac{\pi D_p(P_g)^2}{4} - 0.02\ MPa \frac{\pi D_p(P_g)^2}{4} - 0.14\ MPa \frac{\pi D_p(P_g)^2}{4} - P_{press} \frac{\pi {D_c}^2}{4} = 0$$

Eq (6)

$$(P_г - 0.14\ MPa) \frac{\pi D_p(P_g)^2}{4} = P_{press} \frac{\pi {D_c}^2}{4}$$

Eq (6.1)

When deriving the pressing pressure from equation 6.1 we obtain equation 7 for the pressing pressure in the pressing chamber depending on the gas pressure taking into account the optimal diameter of the piston expander:

$$\boldsymbol{P_{press}(P_g) = (P_g - 0.14\ MPa)\left(\frac{D_p(P_g)}{D_c}\right)^2}$$

eq. (7)

$$\boldsymbol{P_{press}(P_g) = (P_g - 0.14\ MPa)\frac{2\rho_s}{\rho_g(P_g)}}$$

eq. (7.1)

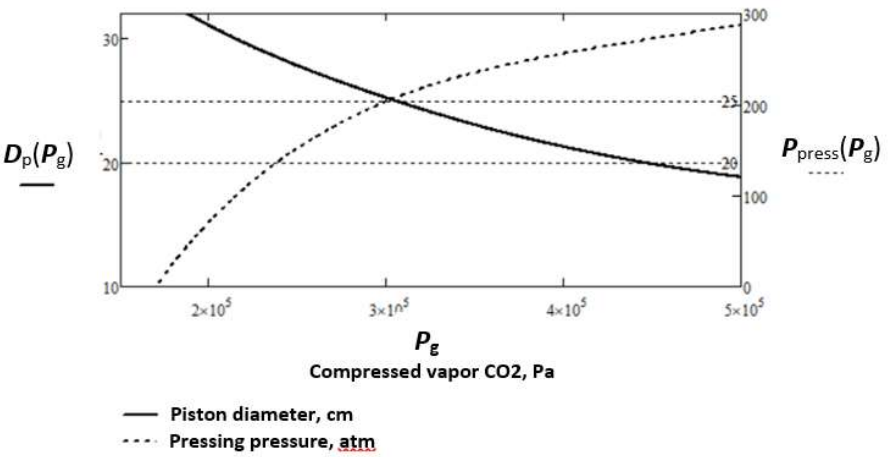

Figure 4. Graphs of equations 4 and 7.1.

Piston diameter, D_p	160 mm	200 mm	160 mm (tandem)	250 mm	320 mm
Gaseous CO2 pressure, P_g	Above 0.51 MPa	0.45 MPa	0.36 MPa	0.31 MPa	0.19 MPa
CO2 snow pressing pressure, P_{press}	n / a	270 atm	240 atm	210 atm	80 atm

Table 2. Data from the particular examples according to Figure 4.

The horizontal marks correspond to the dimensions of the diameter of standard pneumatic cylinders made according to an ISO 15552 international standard: 160, 200, 250 and 320 mm. Herewith, it should be noted that the closer the gas pressure to the CO2 triple point (0.52 MPa), the higher the probability due to the presence of hydraulic resistance in the liquid phase formation line in the pressing chamber and in the system as a whole, which can adversely affect the operation of the pelletizer. The pressure of 0.36-0.31 MPa is the most optimal from the point of view of safety of the pelletizer and pressing pressure.

CONCLUSION

As a result of the work, two designs of a pelletizer with an optimum diameter of piston expander have been developed. For a pressing chamber with a diameter of 20 mm, the optimum diameter of a pneumatic cylinder with one cavity is 250 mm, and 160 mm with two cavities. These results have been used to design, manufacture and test the experimental samples of a dry ice pelletizer with the function of energy recovery of IRBISTECH LLC in 2019.

ACKNOWLEDGEMENT

We express our gratitude for financial assistance to the Innovation Assistance Fund (www.fasie.ru), the SKOLKOVO Fund (www.sk.ru), the Investment and Venture Fund of the Republic of Tatarstan (www.ivfrt.ru) and Khayrullin A. F. (investor).

LEGEND

P	pressure (MPa)	ρ	density (kg×m^{-3})
T	temperature (K)	d, D, L	linear size (mm)
m	weight (kg)	π	the number PI (3.141592)

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