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DEVELOPMENT OF A TESTING STATION FOR EMPIRICAL VERIFICATION OF THE ALGEBRAIC MODEL OF DRY ICE PISTON EXTRUSION

Jan GÓRECKI*

*Faculty of Mechanical Engineering, Poznan University of Technology, 3 Piotrowo Street, 61-138 Poznan, Poland

jan.gorecki@put.poznan.pl

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Abstract: Efficient use of resources is a very important consideration for every production process, especially where waste materials are used as raw materials. One example of these kinds of processes is dry ice extrusion. Based on the subject literature, it can be observed that the machines available in the market that are used to compress dry ice are characterized by high working force value. This leads to low efficiency of resource consumption, in regards to both electrical energy and carbon dioxide. This paper presents a proposed design of a test stand used for measuring compression force as a function of piston displacement in the course of the dry ice extrusion. The first part of the article presents the testing methodology and test stand design. The second part presents the results of measurement of compression force as a function of piston displacement with three different die types. The results of the study allowed to establish the difference between the values of the measured limit force and the values calculated with an analytical model. The test stand design and the results presented in this paper are important for further research and development works in the area of efficient extrusion and compaction of dry ice.

Key words: dry ice, carbon dioxide, agglomeration, extrusion, compaction

1. INTRODUCTION

The use of waste products from manufacturing processes is very often economically justified as it contributes to waste recovery and allows to reuse of production waste as raw material. A review of the available subject literature demonstrates the availability of insufficient information on the description of various processes applied to non-classic materials, including waste material (Wałęsa et al., 2018; Wojtkowiak et al., 2018). An example of such waste product is carbon dioxide obtained, e.g. from the manufacturing of ammonia compounds (Fig. 1); due to the large amounts of generation, factories are often unable to utilize the entire material for their needs. Consequently, liquefied carbon dioxide (LCO_2) is often sold off to interested third parties (Górecki et al., 2018; 2019a; 2019b; Uhlmann et al., 2010).

Possible applications of LCO_2 include the production of dry ice. This material is obtained in solid form through decompression of the liquid. As a result of an adiabatic process, approximately 50% of the decompressed liquid gets crystallized. The resultant product's temperature is −78.4°C, which sublimates under normal ambient conditions (Górecki et al., 2017; Dzido et al., 2019a; Liu et al., 2012; Mazzoldi et al., 2008; Mikołajczak et al., 2018). Based on these characteristics, the material received its common name of dry ice. It is used mostly in product transportation where low temperatures are required (Dong et al., 2012; Li et al., 2016; Liu et al., 2010; Liu et al., 2017; Masa et al., 2016; Mazzoldi et al., 2008; Otto et al., 2011; Spur et al., 1999; Witte et al., 2017) and for surface cleaning (Dong et al., 2013, Dzido et al., 2019b, Dzido et al. 2021, Masa et al., 2014, Mikołajczak et al., 2018; Muckenhaupt et al., 2019).

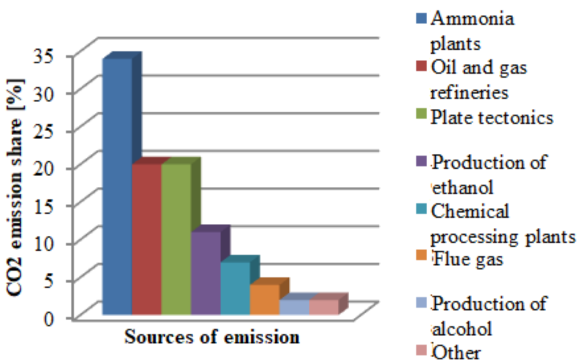

Fig. 1. Main sources of carbon dioxide emissions by percentage share (Górecki et al., 2017)

Extrusion of agglomerated, crystallized carbon dioxide serves to reduce the surface of phase transition, which slows down sublimation and extends the time for which the material stays in solid form (Górecki et al., 2020; Liu et al., 2012).

Various equipment for dry ice extrusion are available in the machine market. The majority of offered solutions utilise piston technology with hydraulic or crank-piston drives. However, there are few sources covering the methods of extrusion or agglomeration of dry ice available in the subject literature (Górecki et al., 2019b; 2020).

Due to the identified deficiency of information regarding extrusion and agglomeration of dry ice as well as considering the peculiar characteristics of the material, it is necessary to carry out scientific works to develop an algebraic model for establishing the resistance force value in multichannel dies (Gorecki et al., 2020b).

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The model provided in this paper is verified only in the laboratory conditions. Therefore, with the intention of employing the model in an industrial environment, it is necessary to develop a suitable testing station to facilitate the study of this kind of environmental condition.

Available subject literature demonstrates a high degree of interest in works aiming to study and develop the shape of the tools used in the process with view of improving product quality as well as the energy efficiency of the process (Dudziak et al., 2017; Dzido et al., 2019a; Górecki et al. 2020a; 2020b; Ishiguro et al., 2020; Kukla et al. 2017; Malujda et al., 2016; Talaśka, 2017; Wałęsa et al., 2019a; 2019b; 2020a; 2020b; Wilczyński et al. 2018; Wilczyński et al., 2019a; 2019b; 2019c; 2020; Wojtkowiak et al. 2019; 2021).

2. BUILDING OF THE TESTING STAND

Fig. 2 provides an overview drawing of the testing station developed by the authors. A vessel with LCO_2 kept at the pressure of 20 bar is attached to the machine. After its decompression in working chamber 2, the material crystallises in fragmented form (Górecki et al., 2017; 2019a). Afterwards, the pneumatic actuator 1 is powered by compressed air and its piston rod 1 moves together with the piston 3. The reduction of volume of the working chamber 2, which contains the crystallised carbon dioxide, leads to the agglomeration of the material. The compaction process continues until the force available on the piston F_T becomes equal to the resistance force F_{OP} associated with the extrusion of the material through the die channel 4 installed at the end of the working chamber 2. After withdrawing the piston to starting position, the device is ready to begin the next work cycle.

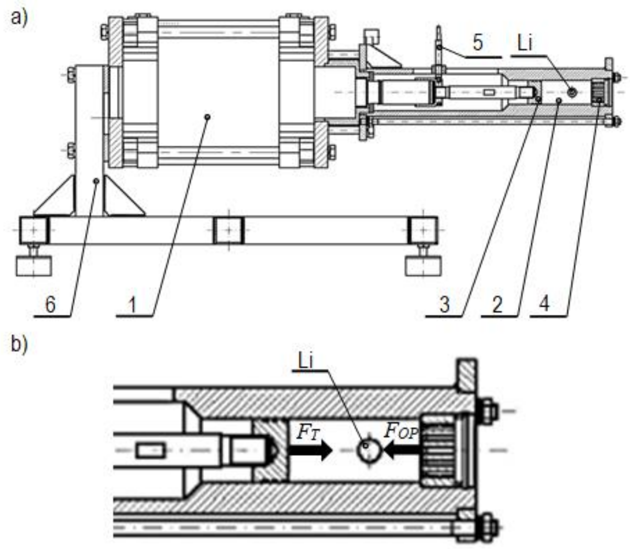


Fig. 2. The working unit of dry ice agglomeration. (**a**) test stand and **(b)** compaction assembly: 1 – pneumatic piston, 2 – working chamber, 3 – compacting piston, 4 – multi-channel die, 5 – displacement sensor grip, 6 – frame. Li, —liquid inlet

The components necessary to carry out the above process that are not provided in Fig. 2 include the unit responsible for the preparation and injection of the LCO_2 as well as the control and measurement instrumentation. Fig. 3 illustrates the interconnections between the indicated components.

3. METHODOLOGY

The testing station is equipped with suitable instrumentation to determine the change of force value applied on the piston F_T as a function of its displacement. Fig. 3 illustrates the schematic view of the station.

The F_T value is determined based on the signal from pressure transducers 12 and 13 placed on both sides of the actuator piston. The measurement of displacement of the compacting piston 3 is achieved by the displacement sensor 5. The transducers are connected to the data acquisition system that includes a data amplifier 19, the signal measurement board 20 and the PC 21.

Fig. 3 presents the automated control system for the testing station. It governs the operation of electrovalve 6, which controls the direction of movement of actuator 1 as well as the LCO_2 injection system electrovalves 11 and 7. The programmable logic controller (PLC) 18 operates the indicated components based on the developed algorithm and signals from limit switches 16 and 17 and the vibrating level sensor 10 controlling the LCO_2 level.

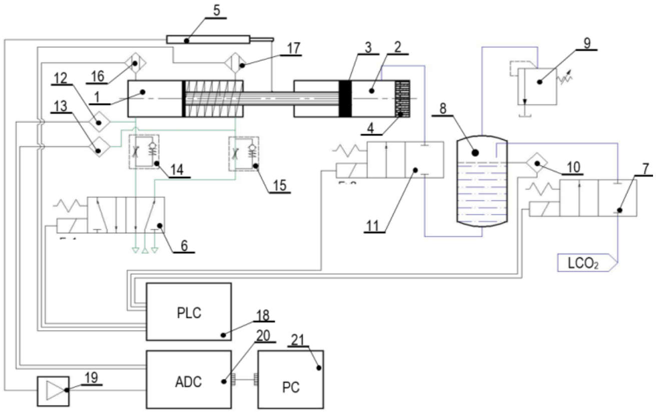


Fig. 3. Schematic view of the carbon dioxide agglomeration station: 1 – pneumatic actuator, 2 – working chamber, 3 – compacting piston, 4 – multi-channel die, 5 – WA-100 displacement sensor, 6 – type 5/2 distributing electrovalve, 7 – refill electrovalve, 8 – liquid CO_2 buffer container, 9 – pressure adjustment valve, 10 – vibrating level sensor for liquid presence, 11 – liquid injection electrovalve, 12, 13 – pressure transducer, 14 and 15 – throttle check valve, 16 and 17 – piston end position sensor, 18 – PLC controller, 19 – measurement amplifier, 20 – signal measurement board, 21 – data acquisition PC

For the purpose of the study, three types of multichannel dies (MCD) with conical-cylindrical channels are used. Each die is characterized by different geometric parameters as provided in Tab. 1 and illustrated in Fig. 4. The die dimensions match the design features of the device, enabling the testing station to be retooled. This allows to compare results with an identical error of measurement resulting from the inaccuracy of pressure transducers equal to 0.01% of the measurement range, i.e. 10 bar. Based on the above factors, it is determined that the pressure measurement error is equal to $|\delta p| = \pm 10\ \mathrm{kPa}$.

The following expression was used to determine the value of available force on the piston,

$$F_T = \frac{(p_1 - p_2)\cdot\pi\cdot(2\cdot R_K)^2}{4}, \qquad (1)$$

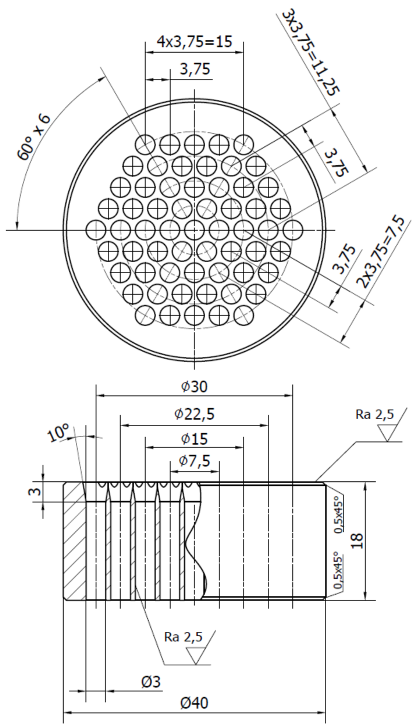
where: R_k – radius of the compacting piston, $R_k = 18\ mm$.

Based on the formula 1, the measurement error value for force F_T was determined using the expression as given below,

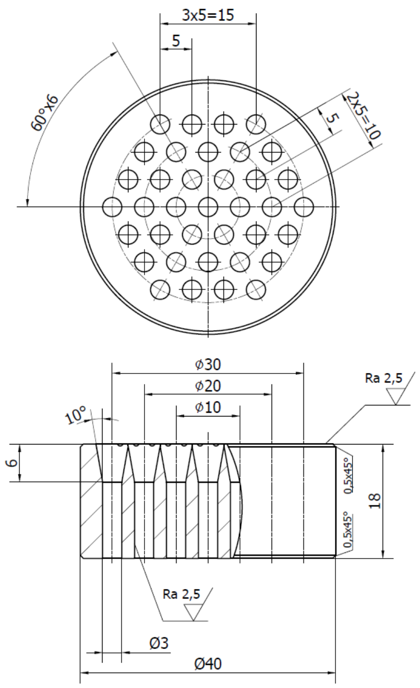
$$|\delta_F| = \frac{(|\delta p_1|+|\delta p_2|)\cdot\pi\cdot(2\cdot R_K)^2}{4} = 20.36 \text{ N}. \quad (2)$$

The established error value for force measurement is deemed sufficiently accurate for employing type A method for result analysis, based on statistical analysis (Arendarski, 2006).

a)



b)



c)

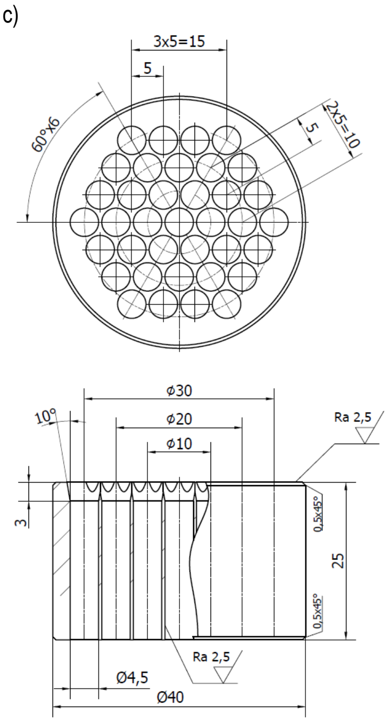


Fig. 4. Multichannel forming dies, a – MCD-0, b – MCD-1, c – MCD-2

Tab. 1. Geometric parameters of the multichannel forming dies, D_{out} – diameter of the channel outlet, *n* – number of channels

	n	D_{out} [mm]	α [°]	*A* [mm]	*b* [mm]	R_K [mm]	*E* [mm]	n_G
MCD-0	61	3		15	3		15	24
MCD-1	37	3	10	12	6	18	15	18
MCD-2	37	4.5		15	3		15	18

4. RESULTS

During the examination, results are recorded from 10 consecutive dry ice extrusion process cycles. The results of the example for the die MCD-0 are provided in Fig. 5 in the form of a line graph presenting the variation of piston force F_T as a function of displacement value *x*.

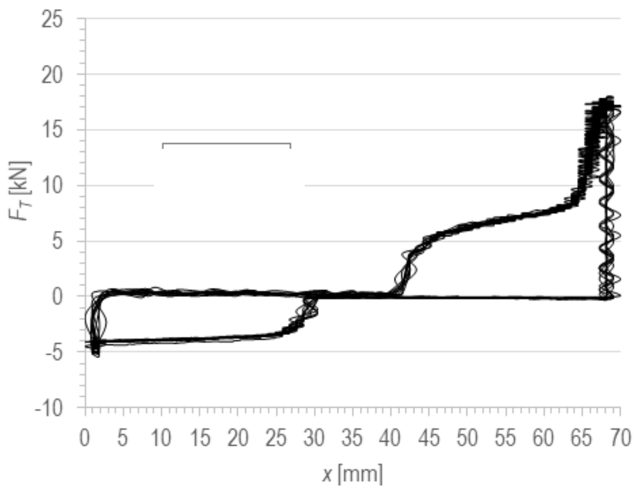


Fig. 5. Results of measuring the force applied to the piston F_T in the course of the extrusion process using MCD-0 die

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The piston withdrawal part of the cycle is excluded from the registered measurements. The results are then averaged in each of the three cases. This allows to identify the characteristics of piston force variability F_T for each die as a function of piston displacement *x*, which are illustrated in Figs. 6–8.

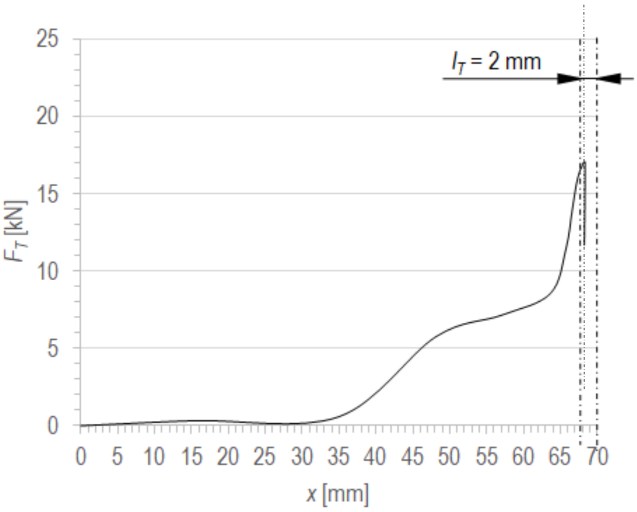

Fig. 6. The characteristic curve for force variation available on the piston F_T as a function of piston displacement *x* in the process of extrusion with MCD-0 die.

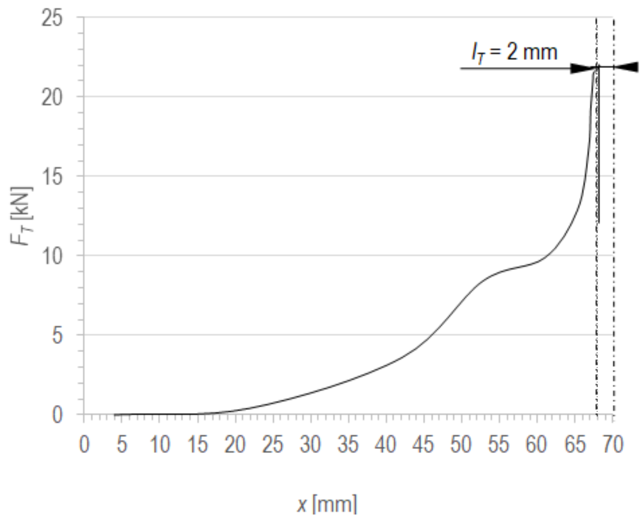

Fig. 7. The characteristic curve of the variation of force available on the piston F_T as a function of piston displacement *x* in the process of extrusion with MCD-1 die.

Based on the developed characteristics, the length of section l_T in the moment of extrusion of the agglomerated material through the die is determined. This parameter has a significant influence on the F_{OP} value and describes the length of agglomerated material along the axis of rotation of the compaction chamber. The influence of this parameter is described in the available literature (Górecki et al. 2017b). The value of limit force during the process utilising MCD-1 die is much higher than that in the processes employing MCD-0 and MCD-2 dies. One of the differences between MCD-0, MCD-1, and MCD-2 die types is the value of parameter b, which influences the shearing stress value as provided in the subject literature (Górecki et al. 2017b; Górecki 2020; Górecki et al. 2020b). Furthermore, the channel outlet diameter D_{out} influences the value of the limit force. The D_{out} parameter relates to the value of cutting edge on the die inlet as well as the force of extrusion resistance. At the beginning of the product formation part of the process, each die channel will shear the agglomerated block of dry ice. The cutting edge parameters relate to the number of channels and the value of D_{out}.

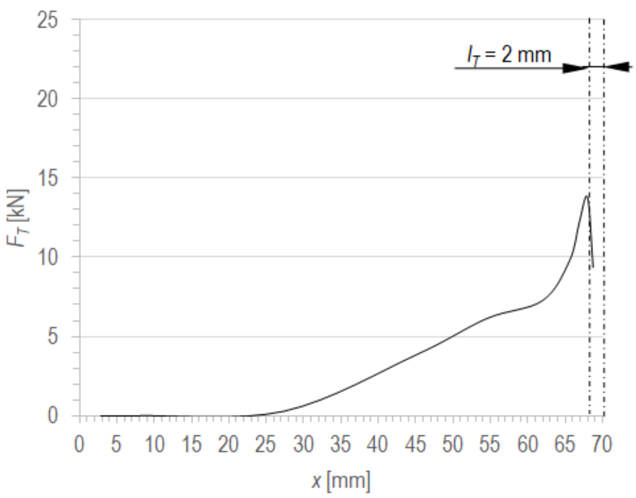

Fig. 8. The characteristic curve of the variation of force available on the piston F_T as a function of piston displacement *x* in the process of extrusion with MCD-2 die.

Test results allowed for comparison of the average limit force value on the piston F_T^{avr} measured during the examination and the results obtained from the algebraic model available in subject literature (Górecki, 2020), which describes the variance of F_{OP} as a function of the geometric parameters of multi-channel dies. See Table 2 for the calculated results together with the maximum measured force value on the piston F_T^{avr}. The information regarding the percentage difference in the force value determined via the algebraic method F_{OP}, and the limit value F_T^{avr} is also provided therein. The value of the difference is calculated using the formula below.

$$\delta = \frac{F_T^{avr} - F_{OP}}{F_T^{avr}} \cdot 100\% \tag{3}$$

Tab. 2. Results of measurement and analytic calculations

Die model	MCD-0	MCD-1	MCD-2
F_{OP} [kN]	14.2	16	10.6
F_T^{avr} [kN]	17.2	21.9	14.2
l_T [mm]	2	2	2
δ [%]	17.4	26.94	25.35

For all three dies, the value does not exceed 27%.

5. SUMMARY

The article presents the results of design works on the testing station, the developed methodology and study results. The examination focussed on identifying the characteristics of force variation on the agglomerating piston as a function of its displacement.

The obtained characteristics are used to determine the limit value of compacting force in industrial conditions. Consequently, the test results could be compared with the results derived from the algebraic model available in the subject literature (Górecki, 2020), which is used to determine the indicated force limit value based on the geometric parameters of multi-channel dies. This allows to determine the difference between results achieved in empirical testing and results derived from the algebraic model available in subject literature, the difference is expressed as a percentage value.

The difference between the calculated and the actual value of the resistance force F_{OP} is affected by the dosing accuracy of the LCO_2, the efficiency of the crystallisation process as well as the resistances effected by the displacement of the agglomerating piston in the device working chamber. According to published studies, the difference in the value derived from the model and the verification tests in laboratory conditions is up to 12.9%. The differences between the algebraic calculation and measurement results obtained from the author's prototype carbon dioxide agglomeration machine are therefore justified. The test result analysis allows to demonstrate that the geometrical parameters of dies influence the limit force during the extrusion process.

The paper presented basic observations regarding the influence of geometrical parameters of multichannel dies on the limit force, which are in line with the conclusion of previous research (Górecki et al, 2019a; Górecki, 2020; Górecki et al. 2020b).

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Jan Górecki: https://orcid.org/0000-0002-4640-7418