The influence of geometrical parameters of the forming channel on the boundary value of the axial force in the agglomeration process of dry ice

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Abstract. The article presents the results of study on the influence of geometrical parameters of the forming channels on axial force which is the main parameter of the agglomeration process of dry ice in the piston method. During research, the material was agglomerated utilizing different dies. The material is characterized by low temperature and sublimation under standard environmental conditions. The study focuses on determining the influence of geometrical parameters of the conical and cylindrical sections of the forming chamber which influence the value of yield stress in the carbon dioxide agglomeration process. The determination of the value of boundary force is the basis for formulating the construction assumptions which shall be the basis for designing and constructing the dry ice compaction and pelletization machine.

Keyword: dry ice, densification, compaction, multichannel die

1 Introduction

The utilization of waste products from manufacturing processes is often economically viable. This fosters the reuse of such waste as raw materials. One of such waste materials is carbon dioxide which is formed e.g. during the manufacturing of ammonium compounds (Fig. 1). However, due to the large amount of waste, factories are often unable to utilize the entirety of the recovered material for own needs. As a result, liquefied carbon dioxide is sold to interested recipients [1-6].

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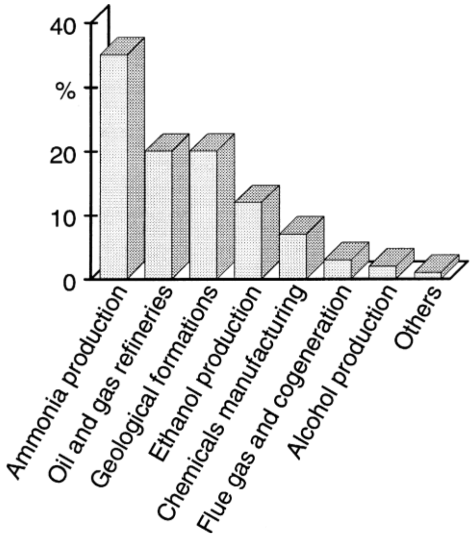

Fig. 1. Share of primary sources in total carbon dioxide production [2]

Liquid carbon dioxide is used, among others, for manufacturing dry ice. This material in solid form is manufactured by expanding the liquid. As a result of adiabatic process, approx. 50% of the expanded liquid crystallizes. The final product temperature is -78.5°C and sublimates in normal environmental conditions [5-11]. Based on the above properties, the material received the popular name of dry ice. It is mostly used in transporting products requiring low temperatures [1, 11-20].

The agglomeration of carbon dioxide serves to limit the surface of the phase transition which slows down the sublimation and increases the time it remains in solid form [2, 10].

There are commercially available devices used to agglomerate dry ice. The majority of the offered solutions utilize piston-based agglomeration with hydraulic or crank-piston drives. However, the available subject literature provides few sources on the dry ice agglomeration technology [2, 8, 21].

The subject matter of the study is the agglomeration process of crystallized carbon dioxide utilizing the piston-based method. The article presents the results of preliminary research on the influence of the geometrical parameters of the multi-channel die on the limit stress value of the compaction process. Subject literature referring to different processes and materials indicates a significant relation between the geometrical parameters of the working system and the necessary force value to carry out the process under consideration [22-27].

In the study, the designed multi-channel dies were utilized, an example construction thereof is shown at (Fig. 2). The geometric parameters of the forming channels have a significant influence on the axial boundary force and transverse dimension of the agglomerate. The aim of the study was to determine the influence of the geometric parameters of multi-channel forming dies on the yield stress value during the compaction process.

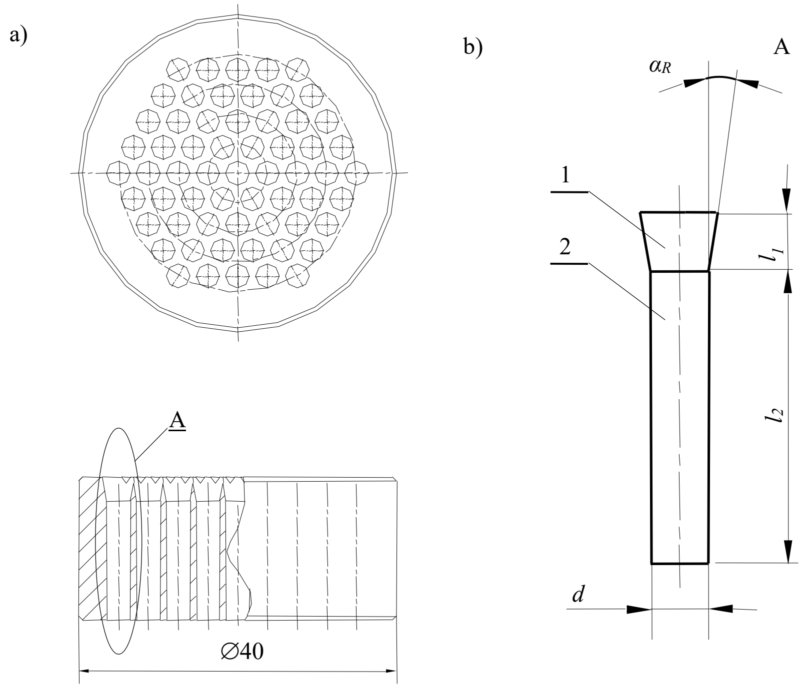

Fig. 2. Example drawing of a multi-channel forming die: a) Forming channel layout, b) forming channel, 1 – conical section of the forming channel, 2 – cylindrical section of the forming channel. α – taper angle of the conical section, l_1 – length of the conical section, d – diameter of the cylindrical section, l_2 – length of the cylindrical section, α_R – side inclination of the conical surface [2]

2 Description of the test procedure

The examination of the geometric parameters of the forming die is performed using the methodology designed based on the sources in literature [1, 21, 28]. The forming die channel is divided into the section with symmetrically convergent conical opening (1) and the cylindrical section (2). The characteristical parameters describing the forming channel were shown on Fig. 2.

According to the designed study methodology, 5 dies were designed and manufactured with assigned designations MK–1 to MK–2. The geometrical parameters of the forming channel are provided in table 1. The MK–2 is the only tested die with no conical section. For other dies, the inclination of the conical section side is equal to α_R.

For testing, a durometer by MTS fitted with a 50 kN a tensometric sensor was employed. During the examination, the force value and displacement of the cross-beam was measured and registered with a constant frequency of 10 Hz. The testing was performed under constant velocity equal to 9 mm/s. The measurements were repeated 10 times for every die.

Table 1. Geometric parameters of multi-channel forming dies.

	MK-1	MK-2	MK-3	MK-4	MK-5
No. of forming channels in the die	61	61	37	37	37
***d* [mm]**	3	3	3	4.5	4.5
Total value of cross-section area of the cylindrical section of the forming channel [mm²]	430.97	430.97	261.41	588.16	588.16
l_1 [mm]	3	0	6	3	3
l_2 [mm]	15	18	12	15	22
α_R [°]	10	-	10	10	10

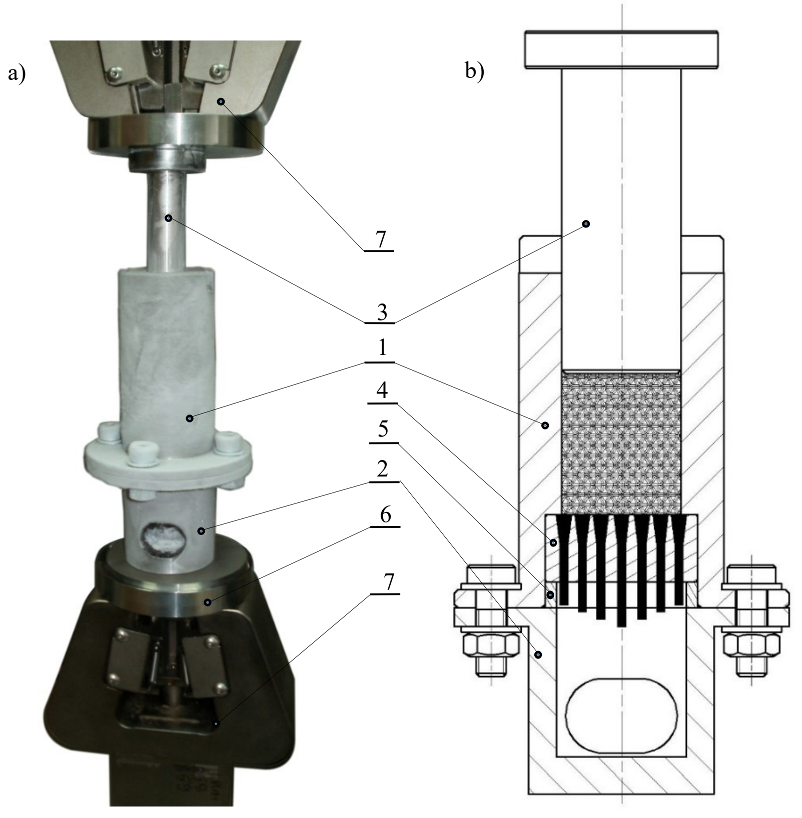

Fig. 3. Measuring assembly: a) grips of strength tester including the testing head and right angle jig, b) testing head cross-section, 1 – compression chamber, 2 – base, 3 – piston, 4 – multi–chamber die forming, 5 – spacer ring, 6 – right angle jig, 7 – grips

Testing utilized the designed and prepared measuring assembly (Fig. 3). The compression chamber (1) was filled with broken down dry ice. The assembly was introduced between the grips of the durometer (7). The forced axial displacement of the compaction piston (3) was accompanied by the compaction of broken down dry ice until yield stress was achieved. Further on, the agglomerate moved through the cylindrical section of the forming channel of the die (4). In order to reduce the error of measurement caused by off-center mounting of the assembly, a jig to ensure right angle alignment was utilized (6).

3 Discussion of the test results

The test results were used to prepare graphs describing the change in value of the force as a function of the durometer cross-beam travel (Figs. 4-8). For every one of the dies with geometric parameters as indicated in table 1, the characteristics were established by determined the limit value of compression force (F_G) and its corresponding displacement. Further displacement of the piston is accompanied by a sudden decrease in compaction force.

The limit point F_G, means overcoming the resistance of agglomeration in the conical section of the forming channel of the die and the beginning of forcing the agglomerate through the cylindrical section. Therefore, the determination of maximum force $F(x)$ at point F_G in this way is equivalent to determining the maximum yield stress at this point.

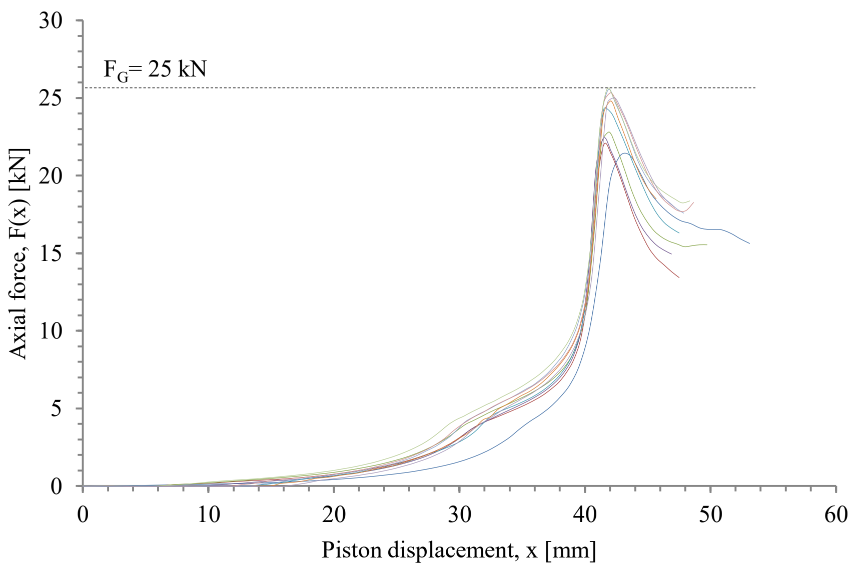

Fig. 4. Variation in axial force depending on the displacement distance of the stamp during the agglomeration process using die MK-1

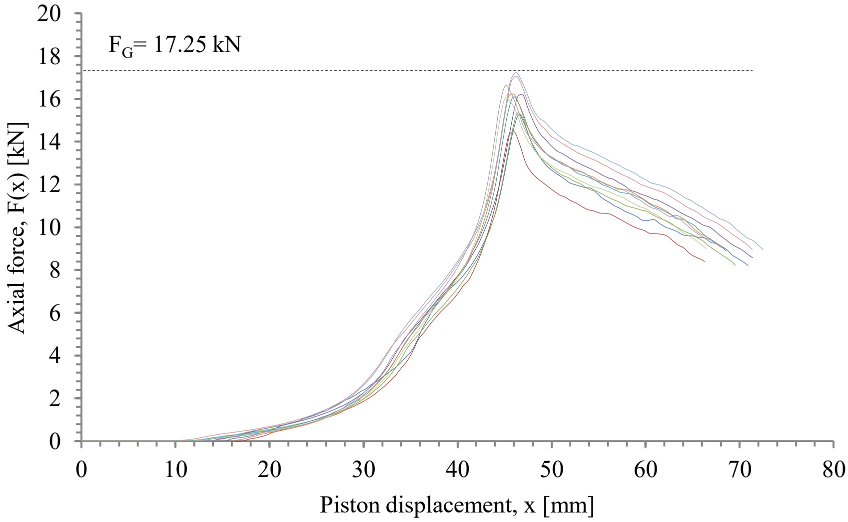

Fig. 5. Variation in axial force depending on the displacement distance of the stamp during the agglomeration process using die MK-2

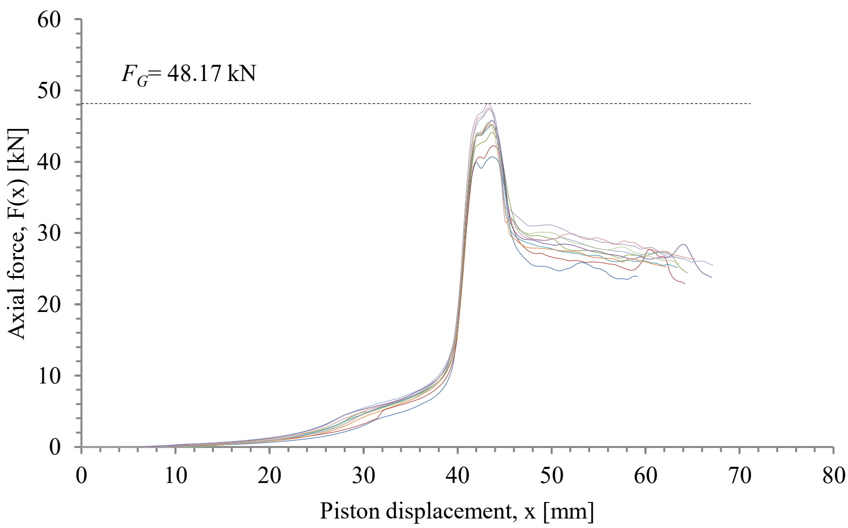

Fig. 6. Variation in axial force depending on the displacement distance of the stamp during the agglomeration process using die MK-3

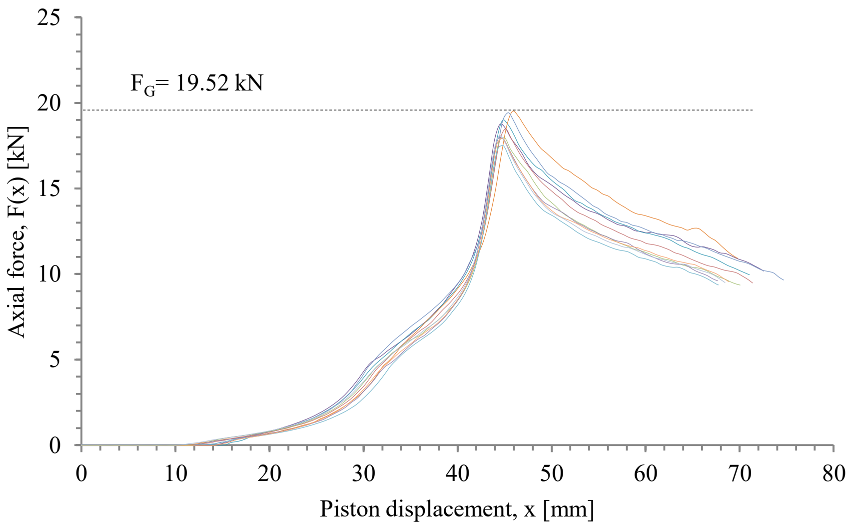

Fig. 7. Variation in axial force depending on the displacement distance of the stamp during the agglomeration process using die MK-4

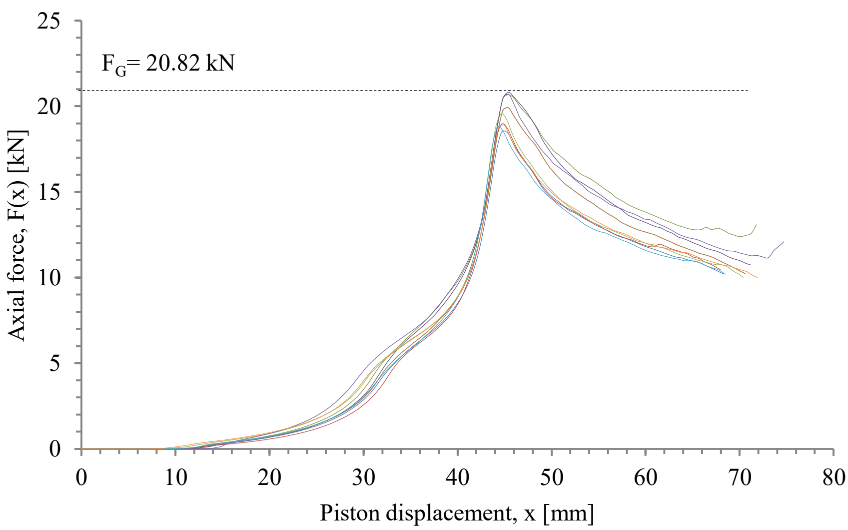

Fig. 8. Variation in axial force depending on the displacement distance of the stamp during the agglomeration process using die MK-5

The average value was used as the estimator for the researched boundary value of the axial force. For every value, measuring inaccuracy was determined, which is equal to non-standard deviation. The estimator values (F_{AVR}) are presented in Table 2. The table also presents the geometrical parameters for every die discussed in chapter 2 of this article.

Table 2. Geometrical parameters of dies and estimate value of boundary force.

	MK-1	MK-2	MK-3	MK-4	MK-5
No. of forming channels in a die	61	61	37	37	37
***d* [mm]**	3	3	3	4.5	4.5
Total value of cross-section area of the cylindrical section of the forming channel [mm^2]	430.97	430.97	261.41	588.16	588.16
l_1 [mm]	3	0	6	3	3
l_2 [mm]	15	18	12	15	22
α_R [°]	10	-	10	10	10
F_{AVR} [kN]	23.1 (2.3)	16.04 (0.85)	45.1 (2.4)	18.45 (0.69)	19.67 (0.87)

Comparing the dies MK–1 and MK–2, one may observe the differences in the geometrical parameter l_1. The change of parameter value affected the estimated boundary force value, where it is greater for die MK–1 in comparison to die MK–2. This is caused by the tapered shape of the conical section in which the variable channel cross-section area along the axis causes secondary compaction of the material. The value is connected, among others with the frictional force which must be overcome by the axial forces in the course of the agglomeration process.

The geometrical parameters of cylindrical sections of forming channels of dies MK–1, MK–3, MK–4 affected the total value of cross-section area of the cylindrical section of the forming channel. Consequently, there is a change in the push-through resistance which must be overcome during the agglomeration process. As a result, the produced agglomerate may be characterized by a varying degree of compaction [2, 28].

The comparison of geometrical parameters of dies MK–4 and MK–5 indicates that the effect of the value l_2 on boundary force value is insignificant. It is caused by the similarity between dry ide and mineral salts which are a material with progressive compaction characteristic [1, 2, 8, 20, 28]. Consequently, the low value of radial forces is observed in the compaction process, which affect the frictional force associated with the agglomerate contacting the side of the cylindrical section.

4 Conclusions

The results of the observations described above allow to determine as follows:
- there is a relation between the cross-section area of the cylindrical section and the boundary force value,
- the boundary compressing force value is affected by the conical section of the die,
- the boundary axial forces are affected by the length of the cylindrical section.

It is observed that the elongation of the cylindrical section causes an increase in the boundary axial force. However, the geometrical parameters do not exhibit a material influence on the value of yield stress of the compaction process.

Together with the change in length of the conical section, one can notice that the ratio of the surface of the entrance and exit areas changes. This ratio has a material influence on the yield stress values which are related, among others, with the degree of compaction of the agglomerate obtained in the process.

The results are insufficient to determine the influence of the inclination angle of the conical section on the value of boundary force. However, it is observed that the geometrical parameters of the conical section of the forming channel of the die are the main influencing factor on the boundary force value.

Based on the observation carried out during the attempt to utilize the designed working system of the industrial machine, it was determined that the die MK-2 does not allow to produce pellets with sufficient cohesion to manufacture units with length greater than the diameter.

The study should be continued in order to determine the influence of the value of the angle of convergence on axial forces. Continuing the study allows to formulate a mathematical model describing the influence of geometrical parameters of the forming die channels on the energy consumption of the dry ice agglomerating machines.

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