Preliminary analysis of the sensitivity of the algebraic dry ice agglomeration model using multi-channel dies to change their geometrical parameters

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Abstract. The article presents the results of a preliminary analysis of the algebraic sensitivity of the model describing the change in the limit values of densification stress in the process of dry ice agglomeration using multi-channel dies in the piston technique. In the available literature, it was noted that the limit value of compaction stresses significantly exceeds the effective value. This justifies the sense of undertaking work on the development of a multi-channel die that allows the reduction of the value of the indicated stress, which will reduce the consumption of electricity necessary for the production of dry ice pellets. The sensitivity analysis performed is related to the attempt to determine the significance of the impact of individual geometric parameters of the multi-channel die on the value of the limit stress. The results will significantly contribute to the development of a work program related to the optimization of geometrical parameters of the tools used to implement the indicated process.

1. Introduction
Modern economy often emphasizes the utilization of waste materials from the manufacturing processes as a major factor in the economic balance. Very often such materials become a side product with numerous interested recipients [1–3]. Among such materials, we have the crystallized carbon dioxide which is a waste product in the ammonia manufacturing process [3]. This material is compressed and delivered in liquid form to interested recipients. Due to sudden expansion of liquid carbon dioxide, it crystallizes [4, 5]. The resulting product is fragmented and features peculiar characteristics in relation to its low temperature of approx. -78.5 °C and sublimation in normal conditions [6–8]. The indicated properties allow for a broad industrial application of the material, e.g. in refrigeration, in transportation of thermolabile materials, disinfection and surface cleaning [8–13].

The efficiency of processes employing dry ice very often depends on sublimation time [3, 7, 14]. Therefore, the fragmented material is subject to agglomeration under pressure to limit the surface area for phase transition to extend its time. Machines for dry ice agglomeration are available commercially. The examination of available machines indicates that in most cases the piston method of agglomeration is employed. The method utilizes special assemblies fitted with multi-channel dies, whose example is illustrated in figure 1.
The geometric parameters of multi-channel dies influence the final form of the compressed dry ice together with the resistance force arising in the process of agglomeration. The force value is directly related to the consumption of electrical energy powering the machine during use. Both factors directly affect the cost-efficiency of the dry ice compaction process, which justifies the need to carry out research and development efforts to improve the manufacturing efficiency. Additionally, the recipients of dry ice are interested in receiving high quality material which is measurable through the density of agglomerated material. The maximum value is 1650 kg m$^{-3}$ and is achieved at limit compaction stress value equal to or greater than 14 MPa [14, 15]. Available literature observes that the limit value of densification stress significantly exceeds the effective value of 14 MPa, which justifies the need for the carried out study [14, 16, 17]. Both needs cited above can be fulfilled by means of the performed research and development works, potentially leading to the development of a new methodology of design of forming dies.

Available subject literature demonstrates a high degree of interest in works aiming to study and develop the shape of the tooling used in the process in order to improve the quality of the product as well as energy efficiency of the manufacturing process [18–32]

2. Algebraic model

Multi-channel dies with their geometric parameters are illustrated on figure 2. One of the views illustrates a forming channel consisting of a cylindrical and convergent, circular symmetric shape sections. The difference in results of the model was compared in literature to the results of empirical testing in laboratory conditions, enabling to determine the error rate not exceeded 9.5 % [17]. This allows to assume that the accuracy thereof is sufficient for the purpose of preliminary analyses of its susceptibility to variance of geometrical parameters.

The presented model indicates the $F_{OP}$ value depends on the value of 12 parameters, thus enabling to formulate the following function:

$$F_{OP} = f(k_T, \mu_T, R_{in}, R_{out}, n, \alpha, a, b, l_T, R_C, e, n_g)$$

(1)

In a multi-channel die, there is a co-dependency between the values of individual geometrical parameters which allowed to formulate the following mathematical relationships:

$$R_{in} = R_{out} + b \cdot \tan \alpha$$

(2)

$$e = R_C - R_{in}$$

(3)

$$n_g = 6\left\lceil \frac{e}{2R_{in}} \right\rceil - 1$$

(4)

$$n = f(R_C, R_{in})$$

(5)
The use of presented functions allows to simplify equation 1 to the below form:

\[ F_{OP} = f(k_T, \mu_T, R_{out}, \alpha, a, b, l_T, R_C) \] (6)

In the simplified equation, it is indicated that the \( F_{OP} \) value varies as a function of 8 parameters, where \( k_T \) and \( \mu_T \) are material constants, which are not subject to the model susceptibility analysis to the variance in geometrical parameters of the multi-channel die. Analogically, the variables \( R_C \) and \( l_T \) constitute geometrical parameters describing the radius of the densification chamber used in the pellet maker as well as the volume of the compressed, crystallized carbon dioxide present in the chamber. Therefore, the indicated parameters were not included in the preliminary susceptibility analysis of the algebraic model because their value is not directly related to the geometrical parameters of the die.

3. Analysis of the sensitivity of the algebraic model

For the purpose of susceptibility analysis of the model to variance in value change of the indicated group of geometrical parameters, an indicator was employed which was the gradient of function variance. It is described by the following formula, with \( x \) parameter value is replaced with the examined variable.

\[ \nabla F_{OP} = \frac{\partial F_{OP}(x)}{\partial x} \] (7)

While determining the individual functions \( F_{OP}(x) \), parameter values provided in table 1 were used.
Table 1. Initial values of the geometrical parameters of the multi-channel die.

| $k_T$ (MPa) | $\mu_T$ | $R_{out}$ (mm) | $\alpha$ (deg) | $a$ (mm) | $b$ (mm) | $l_T$ (mm) | $R_C$ (mm) |
|-------------|---------|----------------|--------------|--------|-------|---------|---------|
| 1.56        | 0.02    | 1.5            | 10           | 3      | 15    | 21      | 36      |

During calculations, only one parameter value was varied, and the variability range of examined parameters was limited to the ranges as provided below, the value of these ranges is based on codependence of individual geometrical parameters of the multi-channel die.

- $R_{out} \in (0.15; R_{in})$ mm
- $\alpha \in (0.01; 17)$ deg
- $a \in (0.01; 50)$ mm
- $b \in (4.5; 10)$ mm

The obtained data allowed to develop characteristics employed to determine an approximation line for the variable $F_{OP}$ values as a function of the examined parameter. For $F_{OP}(\alpha)$, $F_{OP}(a)$, $F_{OP}(b)$ the data set used in calculation was characterized by correlation coefficient not lower than 0.95. Whereas the graph line analysis for the function $F_{OP}(R_{out})$ was limited to the range of 0.5 mm to 2 mm, in which the data exhibited a correlation coefficient value equal to 0.996. This allowed to approximate the graph line with a linear function. The characteristics are shown in figures 3–6.

**Figure 3.** Characteristic of $F_{OP}$ value change as a function of $R_{out}$.

**Figure 4.** Characteristic of $F_{OP}$ value change as a function of $\alpha$. 
Figure 5. Characteristic of $F_{OP}$ value change as a function of $a$.

Figure 6. Characteristic of $F_{OP}$ value change as a function of $b$.

Table 2 shows the value of the unicriterion model susceptibility coefficient based on the illustrated characteristics.

|                    | $\nabla F_{OP} = f(R_{out})$ | $\nabla F_{OP} = f(\alpha)$ | $\nabla F_{OP} = f(a)$ | $\nabla F_{OP} = f(b)$ |
|--------------------|----------------------------|------------------------------|---------------------|---------------------|
|                    | (N mm$^{-1}$)              | (N/$^{\circ}$)               | (N mm$^{-1}$)       | (N mm$^{-1}$)       |
| $\nabla F_{OP}$    | 3864.1                     | 0.7642                       | 32.819              | 1.7386              |

4. Conclusions
The developed results of a preliminary analysis of the algebraic model susceptibility allows to formulate the following conclusions:

- Comparing the results for parameters $R_{out}$, $a$ and $b$, it is observed that the highest influence on the $F_{OP}$ value is exhibited by $R_{out}$.
- Parameter $b$ has negligibly small influence in comparison to other parameters measured in N mm$^{-1}$.
- Parameter $\alpha$ is described in units N$/^{\circ}$, therefore value comparison cannot provide unambiguous results in regards its relevance for the determination of the $F_{OP}$ value.
The formulated conclusions indicate that when designing multi-channel dies allowing to agglomerate dry ice at the effective value of densification stress one needs to begin with determining the correct value of $R_{\text{out}}$. Whereas during subsequent stages of design work, it is necessary to determine the values of $a$ and $\alpha$ parameters.

The developed results and conclusions will be utilized in further studies on the optimization of multi-channel dies used for agglomeration of crystallized carbon dioxide. Further actions planned in relation to the developed algebraic model involve:

- The optimization of shape of the multi-channel die with cylindrical-conical channels.
- The development of an algebraic model for multi-channel dies with different shapes of the conical section.
- The examination of the possibility to adapt the examined model to other fragmented materials.

5. References

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