Preliminary analysis of the sensitivity of the FEM model of the process of dry ice extrusion in the die with a circularly converging channel on the changing its geometrical parameters

J Górecki
Faculty of Mechanical Engineering, Poznan University of Technology, 3 Piotrowo, Poznan, Poland

Corresponding author e-mail address: jan.gorecki@put.poznan.pl

Abstract. The article presents the results of a preliminary analysis of the numerical model susceptibility for simulating the process of dry ice compaction utilizing single-channel and multiple channel dies. The work focuses on a preliminary comparison of the influence of changes in the geometrical parameters of the 4 types of compression channels. Based on the results of the performed analyses, conclusions were formulated for a basis and direction of further study regarding improving the energy efficiency of the indicated manufacturing process.

1. Introduction
In contemporary economy, a very important consideration in the economic balance is the utilization of waste material from manufacturing processes. Very often, there will be buyers interested in these side products [1-3]. Crystallized carbon dioxide can be classified among such materials, which is a waste product in the production of ammonia [3]. The material is pressurized and delivered to interested parties in liquid form. As a result of sudden expansion, liquefied carbon dioxide crystallizes [4, 5]. The product of this process is fragmented and exhibits peculiar characteristics in regards to its low temperature of approx. - 78.5 °C, and sublimation under normal conditions as shown in Fig. 1 [6, 7]. The indicated characteristics enable diverse industrial application of this material, e.g. in refrigeration, transportation of thermolabile materials, disinfection and surface cleaning [7-11].
The efficiency of cooling processes employing dry ice are dependent on sublimation time [6,12]. Therefore, the fragmented material is subjected to high pressure agglomeration which reduces the area of the phase transition and increasing of that time. Equipment for dry ice agglomeration is available commercially. The examination of available machines indicates that piston-type solutions are employed the most often. This working method utilizes special systems equipped with multi-channel or single-channel dies (Fig. 2).

The geometric parameters employed in the dies affect the values of resistance forces arising in the process of agglomeration and forming. This is related to two requirements which are at odds with one another. The manufacturers of compacted dry ice are interested in reducing the energy consumption required for carrying out the process and strive to manufacture extruded material with as high density as possible, which is considered to be the quality parameter of the process. This requirement can be fulfilled as a result of developing a new method of die design.

As part of the works carried out in relation to improve the design method, a numerical model was developed, the results obtained via this model were confirmed empirically (Górecki et al., 2019).
the course of further development of works presented in this article, results of application of the established model are presented for the shaping of forming dies of type not available commercially: C02, C03, C04. The illustration of different types of analyzed extrusion tubes together with their geometric parameters are shown on Fig. 3.

**Figure 3.** Extrusion tubes with different types of diameter reduction from $D_{in}$ to $D_{out}$: a) conical shape channel – type C01, b) tube with concave-convex shape of diameter reduction – type C02, c) tube with convex shape of diameter reduction – type C03, d) tube with concave shape of diameter reduction – type C04

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 [15-38].

2. FEM model

The FEM model has two constituents. The first one being an appropriately formed channel, defined as rigid material, the second one is the material of pre-compressed dry ice forced through the die. The material prepared to be forced through the correctly shaped channel was assigned an initial state i.e. the relevant value of hydrostatic pressure. According to the results of earlier study, the effective process calls for pre-compression of the crystallized dry ice utilizing pressure value of 14 MPa. The compaction and forcing through characteristics for the selected multi-channel die, plastic stress value was determined at 2,1 MPa together with elasticity coefficient during compaction in semi-open chamber (combination of compaction in a closed chamber and forcing through a multi-channel die) at
100 MPa. The density of pre-compacted material was assumed at 1625 kg/m$^3$. Fig. 4 shows and example distribution of equivalent stress in the compacted material for the four types of channels.

![Fig. 4. Example stress distribution in compacted material: a) conical tube – type C$_{01}$, b) tube with concave-convex shape of diameter reduction – type C$_{02}$, c) tube with convex shape of diameter reduction – type C$_{03}$, d) tube with concave shape of diameter reduction – type C$_{04}$](image)

3. Sensitivity analysis of models
In order to carry out the model sensitivity analysis, 2 shape indicators were formulated. These will be used to carry out an analysis of resistance force as a function of a common variable for the 4 different tube types.

The first of the indicators is a quotient of initial diameter $D_{in}$ and outgoing diameter $D_{out}$. It was named the diameter indicator $W_{D}$. The value of the second indicator varies as a function of the quotient of the convergent section of the channel $a$ and the length of the cylindrical section $b$. It was named the length indicator $W_{L}$.

Additionally, a third indicator was formulated, which might be used in the analysis for channel types C$_{03}$ and C$_{04}$. Its value changes as a function of the quotient of initial diameter $D_{in}$ and the radius of curvaceousness $R_{1}$. It was named the curvaceousness radius indicator $W_{RK}$.

Utilizing the developed model, simulations of different indicator values were carried out. Figs. 5-9 present the results.
Figure 5. $F_{OP}$ values as a function of the length indicator $W_L$, for channels: C$_{01}$, $W_D$ = 1,353, C$_{02}$, $W_D$ = 1,353

Figure 6. $F_{OP}$ values as a function of the length indicator $W_L$, for channels: C$_{03}$, $W_D$ = 1,353, C$_{04}$, $W_D$ = 1,353

Figure 7. $F_{OP}$ values as a function of the diameter indicator $W_D$ for channels: C$_{01}$, $W_L$ = 5, C$_{02}$, $W_L$ = 5
Figure 8. $F_{OP}$ values as a function of the diameter indicator $W_D$ for channels: $C_{03}$, $W_L = 5$

Figure 9. $F_{OP}$ values as a function of curvaceousness radius indicator $W_{RC}$ for channels: $C_{03}$, $W_L = 5$, $C_{04}$, $W_L = 5$

For the purpose of comparison of the influence of individual indicator values on the resistance force value $F_{OP}$ an approximating equation was determined for the variance of $F_{OP}$ value as a function of a specific indicator. The developed equations allowed to determine the value of the model sensitivity indicators as described in the equation below (refer with eq. 1),

$$\nabla f (W_X) = \frac{\partial f (W_X)}{\partial W_X}$$

(1)

The calculated values are presented in Tab. 1.

| Table 1. Model sensitivity indicators |
|--------------------------------------|
| $\nabla f (W_L)$ | $\nabla f (W_D)$ | $\nabla f (W_{RC})$ |
|------------------------------|-----------------|-----------------|
| $C_{01}$                    | 2.64            | 139.6           | –               |
| $C_{02}$                    | 1.79            | 182.7           | –               |
| $C_{03}$                    | 2.67            | 148.0           | 0.38*           |
| $C_{04}$                    | 1.76            | –               | 0.93            |

* – value determined for $\nabla f (W_{RC})$ at $W_{RC} \in 0.89$ to 2.7
4. Conclusions
Based on the comparison of the result of the described and presented model sensitivity values, it was determined that the value $W_D$ affects the value more significantly than $W_L$. The $W_RC$ indicator was relevant for channels C03 and C04, in the course of the examination it was determined that its variance does not materially affect the resistance force value $F_{OP}$.
For future works on the optimization of the geometric parameters of the channels, preliminary analysis should focus on the $W_D$ indicator.
In the case of difference of value for sensitivity indicators for individual types of channels, it is equal of up to 34%. At the current stage of research, this does not allow to limit the consideration to only one type of forming channel.
The presented research is a part of an R&D project with the main goal is finding geometric parameters with allow to improve the efficiency of the compaction and extrusion process of dry ice.
In the project are used FEM analysis with implemented genetic methods. This solution allows conduct research in a wide range of potential domains to solve. Therefore, at this stage, there is no need to limit the types of shapes of the die channels.

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