METHODOLOGY ASSESSMENT OF THE GATING SYSTEM NUMERICAL DESIGN OF HIGH-PRESSURE DIE CASTING WITH REGARD TO THE MATERIAL APPLICABILITY

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High pressure die casting is a precision casting method that comes closest to the ideal effort of directly transforming the base material into a finished product. Casts produced by high pressure die casting are characterized by high quality, even if they are prone to internal inhomogeneity. The internal inhomogeneity of the casts is, among other things, caused by entrainment of air, gases and vapors inside of the gating system by the melt and their entrapment in the melt volume and distribution in the mold cavity, and thus also in the volume of the cast. The primary factor in reducing the gas and vapors entrapment by the melt is the correct design of the gating system. In general, the geometry of the gating system depends on the design of the cross-section of the gate. Calculation of the gate area is not explicitly determined and there are several mathematical formulations for its determination. The submitted article describes the methodology of the gating system design and assessment of selected methods of gate geometry calculations with regard to the subsequently determined volume of the gating system, the utilization of the metal batch per one operation and the size of the necessary machine locking force.

KEYWORDS

HPDC, Gating Systems, Aluminium Casts, Gating System Design

1 INTRODUCTION

High pressure die casting is a production method of almost pure complex shapes of geometric parts for a wide industrial spectrum at relatively low production costs [Zhao 2018]. In this foundry technology, liquid metal is press into a mold cavity at high speed (30 – 100 m/s) and high pressure through a complex motion system. The geometry complexity of casts and gating systems leads to significant three-dimensional flow of the melt and to sprays [Qin 2019, Cleary 2014]. It is this irregular formation of the melt stream when passing through the runners that causes the most common defect of high pressure die casting, porosity. It significantly penetrates the inner part of the homogeneity of the casts, which is manifested by a decrease in the quality and mechanical properties of the casts [Matejka 2021, Tavodova 2022].

The primary factor influencing the entrapment of gases contained in the mold cavity by melt and their subsequent transport into the cast volume in the gating system and its design. The design of intelligent gating system is the key part of the intelligent and economically efficient casting [Gou 2024, Cao 2018]. Typically, the design of a gating system is based on decades of engineering experience and empirical rules that have been refined through many trials during the development of HPDC technology. The most common method of optimizing the gating system is manual design. Inadequate design of the gating system can cause turbulence, shrinkage porosity, blisters, hot tearing, surface roughness and other defects [Sukhodub 2018, Hren 2020, Minamide 2023].

The general principles for the gating system design in the conditions for Czech Republic are summarized in the standard CSN 22 8601 [CSN 22 8601 1984]. The design of the gating system dimensions depends on the dimensional and volume parameters of the cast on the basis of which the area of the gate is determined. The calculation of the cross-sectional areas of the main and secondary runners depends on the area of the gate. This standard provides as a default parameter determining the dimensions of gate the filling time of the mold cavity and the melt velocity in the gate. For the design of the runners, the minimum ratio of the gate area and the cross-section of the runner before opening into the gate is given. The recommended values of the parameters are given in permissible intervals bounded by the maximum and minimum permissible values. The possibility of a correct selection is limited by the experience of the designer, and therefore introduces the risk of error in the calculation [Majernik 2019]. Although this standard has an earlier publication date, it has not yet been cancelled or replaced by another standard. In general, it is based on the principles and conclusions conceived by the authors Pisek [Pisek 1956], Sebl [Sebl 1961 and 1962] and Valecky [Valecky 1963].

The error caused by the selection of input parameters in the design by selecting from the prescribed interval according to the standard CSN 22 8601 [CSN 22 8601 1984] is eliminated by the calculation formulated by J. F. Wallace and E. A. Herman presented in the Gating Manual, published under the auspices of NADCA [NADCA 2006 and 2015].

In the monograph Influence of Structure Adjustment of Gating System of Casting Mold upon the Quality of Die Cast the collective of authors proceeded from the above-mentioned methods of designing the gating systems and compiled the design methodology according to which the gating system was designed for the cast in the mentioned monograph examined [Gaspar 2017]. This methodology was subsequently revised, expanded and supplemented by the principles of designing the components for high pressure die casting by the collective of above-mentioned authors and published in the monograph Design of Casting and Gating Systems – Primary Prediction of Quality of Die Casting Components [Majernik 2021].

The submitted contribution is based on the methodologies conceived in publications [CSN 22 8601 1984, Majernik 2019 and 2021, NADCA 2006 and 2015, Gaspar 2017]. Simultaneously, it also takes into account the part of the methodology from the publication by author Ragan [Ragan 2007]. For a specific type of the cast, in accordance with the methodology for designing the gating systems for high pressure die casting based on the above cited publications, calculation of five designs of the gating systems is made using the variables recommended variants of the gate cross-section design S_G and the input parameters of calculation. The very design of the dimensions of the gating system depends on the design of the gate cross-section S_G. To determine this value, in accordance with the NADCA association and according to the literature [NADCA 2006 and 2015], it is necessary to determine the filling time of the mold cavity t and the melt velocity in the gate v_G. These input parameters are also used to determine the gate cross-section SG according to the CSN 22 8601 standard (More precisely, two of the recommended relations. Additional mathematical derivations, as will be presented below, are simplified formulations for aluminium-based casts of a lower weight category.) [CSN 22 8601 1984]. The values of the mold cavity filling time t and the melt velocity in the gate v_G are determined by the standard CSN 22 8601 [CSN 22 8601 1984] only as a guideline, within a certain recommended range. This range of recommended values introduces considerable inaccuracy into the design of gating systems, especially in the case of young designers. Partially, it is possible to determine the values of the mold cavity filling time t and the melt velocity in the gate v_G based on empirically created graphs of the dependence of the monitored parameters on the dimensions of the cast found in the literature [Valecky 1963, Ragan 2007], which are also presented in [Majernik 2021]. For a more accurate calculation of the filling time of the mold cavity t a relation is introduced in accordance with the NADCA association and according to the literature [NADCA 2006 and 2015] and the velocity of melt in the gate v_G can be derived according to the literature [Gaspar 2017, Majernik 2021] (all relations, diagrams and mathematical derivations a presented below).

The aim of the contribution is to compare the individual relations for calculation of the cross-section of the gate S_G with regard to the resulting dimensions and geometry of the gating systems. The determination of the input technological parameters for the calculation of the gate cross-section S_G, namely the filling time of the mold cavity t and the velocity of the melt within the gate v_G is performed numerically according to [NADCA 2006 and 2015, Gaspar 2017, Majernik 2021]. In order to verify the suitability of determining the filling time of the mold cavity t and the velocity of the melt within the gate v_G based on empirically derived graphical dependencies according to [Valecky 1963, Ragan 2007], a numerical design of the dimensions of the gating system is performed using the input parameters t and v_G from these graphs. The comparison of numerical designs is performed with the regard to the recommended values of t and v_G in accordance with the CSN 22 8601 standard [CSN 22 8601 1984], the total volume of the gating system, the utilization of the metal batch for one operation and the size of the minimal necessary pressure of the casting ma-chine with cold horizontal filling chamber.

2 DESCRIPTION OF EXPERIMENTAL PROCEDURE

2.1 *General recommendations and formulations for the gating systems designs*

In general, it is possible to divide the numerical design of the dimensions and geometry system into following steps:
- determination of the filling time of the mold cavity t;
- determination of the velocity of the melt in the gate v_G;
- determination of the overflow's volumes V_O;
- determination of the cross-section of the gate S_G;
- determination of the cross-section of runners S_{SR}, S_{MR};
- determination of geometric characteristics and design solution of gating system parts.

2.1.1. Determination of the filling time of mold cavity t

The quality of the cast surface and its internal homogeneity are strongly influenced by the filling time of the mold cavity. If the filling time is too short, gases and vapors are insufficiently removed from the mold cavity, which leads to increased porosity of the casts, even if the surface looks good. On the other hand, if the filling time is too long, the gases are ventilated, but due to the decrease in the temperature of the alloy at the face of the flow, there will be no perfect connection of the flows, which leads to the formation of clod joints and internal lumps [Minamide 2023, Ignaszak 2015].

CSN 22 8601 standard [CSN 22 8601 1984] lists the recommended values of the filling time of mold cavity derived from the prevailing thickness of the cast wall according to Tab. 1.

Table 1. Recommended filling times of mold cavity

Predominant casts wall thickness h_{CH}, mm	A
< 1.5	0.01 – 0.03
< 1.8	0.02 – 0.04
< 2.0	0.02 – 0.06
< 2.3	0.03 – 0.07
< 2.5	0.04 – 0.09
< 3.0	0.05 – 0.10
< 3.8	0.05 – 0.12
< 5.0	0.06 – 0.20
< 6.3	0.08 – 0.30

A relatively wide range of values for the filling time of the mold cavity according to Tab. 1. can lead into a significant error rate in numerical geometry design of gating system. On the basis of numerous calculations and experiments, the dependence of the optimal filling time on the characteristic wall thickness was construct-ed and is presented in Fig. 1 [Valecky 1963, Majernik 2021, Ragan 2007], which can help to more accurately determine the optimal filling time t.

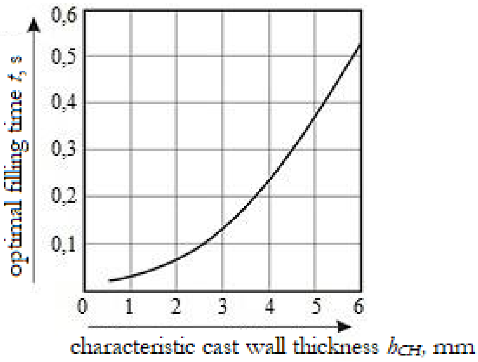

Figure 1. Dependence of the optimal filling time on the characteristic cast wall thickness [Valecky 1963, Majernik 2021, Ragan 2007]

A more accurate way to determine the filling time of mold cavity is given by relation (1) compiled and used in the Gating Manual from NADCA [NADCA 2006]. In this relation, the filling time of mold cavity t is determined not only on the basis of the characteristic cast wall thickness h_{CH}, but also takes into the account the thermal and thermal-physical characteristics of the mold and melt.

$$t = K * \left\{\frac{T_G - T_{LIK} + S * Z}{T_{LIK} - T_D}\right\} * h_{CH} \quad (1)$$

Where:

t – filling time [s],

T_G – melt temperature in the gate [°C],

T_{LIK} – liquidus temperature [°C],

T_D – mold temperature [°C],

S – permissible percentage of melt solidification at the end of the mold cavity filling [%],

Z – conversion factor of solid particles related to the range of solidification [°C/%],
K – empirically derived constant related to the conductivity of the mold [s/m],
h_{CH} – characteristic casts wall thickness [m].

The constant K takes on the following values:
- 0.0312 s/mm between AISI P-20 steel (pre-hardened nitrided steel for plastic injection molds) and zinc alloys,
- 0.0252 s/mm between steels AISI H-13 (alloy of steel and chromium) and AISI H-21 (alloy of steel, chromium and tungsten) and magnesium alloys,
- 0.0346 s/mm between steels AISI H-13 and AISI H-21, aluminium and brass alloys,
- 0.0124 s/mm between alloys of tungsten and magnesium, zinc, aluminium and brass [Majernik 2019, NADCA 2006].

The following Tab. 2 depicts the permissible values of material solidification depending on the casts wall thickness h_{CH}.

Table 2. Permissible values of melt solidification S depending on the casts wall thickness h_{CH}

Predominant cast wall thickness h_{CH}, mm	Permissible values of melt solidification S, %		
	Aluminium	Magnesium	Zinc
< 0.8	5	10	5 - 15
0.8 - 1.25	5 - 25	5 - 15	10 - 20
1.12 - 2	15 - 35	10 - 25	15 - 30
2 - 3	20 - 50	20 - 35	20 - 35

The constant Z takes on following values:
4,8 °C/% for aluminium alloys ASTM 360, 380 and 384, all hypoeutectic AlSi (Cu/Mg) alloys containing less than 12 % silicon,
5,9 °C/% for aluminium alloys ASTM 390, hypereutectic alloys AlSi (Cu/Mg),
3,7 °C/% for magnesium alloys,
3,2 °C/% for zinc alloys 12 and 27,
2,5 °C/% for zinc alloys 3, 5 and 7,
4,7 °C/% for brass.

2.1.2. Determination of melt flow velocity in the gate v_G

The mechanical properties and quality of the casts are largely influenced by the melt flow velocity in the gate v_G. Modern high pressure die casting machines can achieve velocities in the gate of up to 100 ms^{-1}, but the molds begin to degrade at approximately 40 ms-1. For this reason, it is not practical to determine the flow velocity in the range of 40 - 100 ms^{-1}. To reduce the porosity in cast, caused by the air entrapment, the gating system and gates can be optimized so that the melt does not flow through the system too quickly and there are no sudden changes in the flow directions that could cause the backflow and mixing of the melt. [Gaspar 2016, Gaspar 2019].
Standard CSN 22 8601 [CSN 22 8601 1984] lists the recommended melt velocities in the gate v_G for individual types of alloys of cast according to Tab. 3.
A relatively wide range of melt velocity values in the gate according to Tab. 3 can introduce a significant error rate into the numerical design of the gating system geometry. On the basis of numerous calculations and experiments, the dependence of the optimal melt velocity in the gate on the characteristic cast dimensions was constructed and presented in Fig. 2 [Valecky 1963, Majernik 2021, Ragan 2007], which can help to more accurately determine the optimal melt velocity in the gate v_G, $m.s^{-1}$.

Table 3. Recommended melt gate velocity

Alloy	Gate velocity v_G, $m.s^{-1}$	
	Normal casting	Vacuum casting
Zn	20 - 30	---
Al	20 - 60	15 - 30
Mg	40 - 90	---
Cu	20 - 50	---

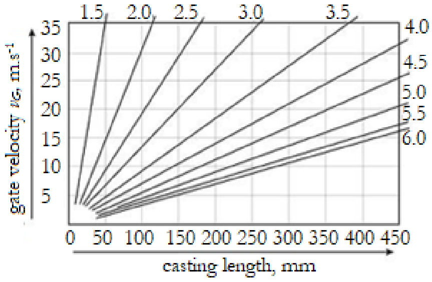

Figure 2. Dependence of the optimal gate velocity on the characteristic dimensions of the cast [Valecky 1963, Majernik 2021, Ragan 2007]

A more precise possibility of determining the melt velocity in the gate is given by relation (2) [gaspar2017, Majernik 2021]. In this relation, the melt velocity in the gate v_G is determined not only on the basis of the cast characteristic dimensions, but also takes into account the filling time of the mold, the density of the alloy and the filling chamber design.

$$v_G = \frac{m_C}{\rho * t * d_p * 0.785} \quad (2)$$

Where:
v_G – gate velocity [$m.s^{-1}$],
m_C – weight of cast [kg],
ρ – melt density [$kg.m^{-3}$],
t – filling time [s],
d_p – diameter of the pressing piston [m],
0.785 – constant

2.1.3. Determination of overflow volume V_O

The overflow, or venting hole, serves as a heat accumulator and storage of low-quality, oxidized metal. Overflows are necessary if the cast wall thickness is low or if it is necessary to allow the cast to solidify at a higher temperature, such as when casting cores located far from the gating system. In such case, the melt surrounds the core with narrow walls from both sides and the temperature must be maintained so that the two streams of melt combine and form a tightly connected, uniform structure of casting. The selection of overflow volume is therefore closely linked to the cast wall thickness and its volume [Minamide 2023, NADCA 2006].
In Tab. 4, the recommended overflow volumes for conventional high pressure die casting machines are stated, depending on the smallest cast wall thickness.

Table 4. Recommended overflow volume

Characteristic cast wall thickness h_{CH}, mm	Overflows volume, percentage ratio out of casts volume, %	
	High surface quality	Lower surface quality
0.90	150	75
1.30	100	50
1.80	50	25
2.50	25	25
3.20	---	---

2.1.4. Determination of gate cross-section S_G

The gate is a limiting element of the gating system, which has a significant impact on the final quality of casts [Zhao 2018]. According to the Gating Manual [NADCA 2006], it is possible to determine the gate cross-section using the following relation (3):

$$S_G = \frac{V_{cast} + V_{overflows}}{t * v_G} \quad (3)$$

Where:

S_G – gate area [m^2]

V_{cast} – cast volume [m^3]

$V_{overflows}$ – volume of overflows [m^3]

v_G – gate velocity [m.s^{-1}],

t – filling time [s].

Correlated with this relation is the relation given by standard CSN 22 8601 [CSN 22 8601 1984], which for the calculation of the gate area states the following relation (4):

$$S_G = \frac{G}{\rho * t * v_G} \quad (4)$$

Where:

S_G – gate area [m^2],

G – sum of cast and overflows weight [kg],

ρ – melt density [kg.m^{-3}],

v_G – gate velocity [m.s^{-1}],

t – filling time [s].

Simultaneously, according to the standard CSN 22 8601 [CSN 22 8601 1984], to calculate the gate cross-section, it is possible to use the relation (5):

$$S_G = \frac{G}{\rho * (k_1 * k_2 * v_t) * (k_3 * k_4 * t)} \quad (5)$$

Where:

S_G – gate area [m^2],

G – sum of cast and overflows weight [kg],

ρ – melt density [kg.m^{-3}],

v_t – gate velocity [m.s^{-1}], standard CSN 22 8601 states for relation (5) v_t = 15 m.s^{-1}

t – filling time [s],

k_1, k_2, k_3, k_4 – coefficients, see Tab. 5 - Tab. 8.

Table 5. Coefficient k_1 values – resulting from the cast wall thickness

Characteristic cast wall thickness h_{CH}, mm	Coefficient k_1
1 – 4 included	1.25
4 – 8 included	1.00
> 8	0.75

Table 6. Coefficient k_2 values – resulting from the applied pressure on the melt

Pressure on melt *p*, MPa	Coefficient k_2
< 20	3.0
20 - 40	2.0
40 - 60	1.0
60 - 80	0.8
80 - 100	0.6
> 100	0.4

Table 7. C oefficient k_3 values – resulting from the type of casting alloy

Alloy based on	Coefficient k_3
Pb, Sn	1.10 – 1.20
Zn	1.00
Al	0.90
Mg, Cu	0.75 – 0.80

Table 8. Coefficient k_4 values – resulting from the ratio of cast wall thickness

Cast wall thickness ratio	Coefficient k_4
even	1.0
uneven	1.5

For casts made of aluminum alloys with low weight from 30 g to 200 g, it is possible to use simplified relation (6) to calculate the gate cross-section, which is also given by standard CSN 22 8601 [CSN 22 8601 1984, Majernik 2021]:

$$S_G = 0.1 * \sqrt{V * e} \quad (6)$$

Where:

S_G – gate area [m^2],

0.1 – constant given by standard CSN 22 8601,

V – sum of cast and overflow volumes [m^3],

e – predominant cast wall thickness [m].

A quick calculation of the gate cross-section can also be performed using the relation (7) stated in [CSN 22 8601 1984, Majernik 2021]:

$$S_G = 0.016 * (V)^{0.745} \quad (7)$$

Where:

S_G – gate area [m^2],

0.016 – constant given by standard CSN 22 8601,

V – sum of cast and overflow volumes [m^3],

0.745 – exponent given by standard CSN 22 8601.

2.1.5. Determination of runner cross-section S_{SR}, S_{MR}

The ratio of runner cross-section SSR (before transition to the gate) to the gate cross-section SG is controlled by the method of casting [CSN 22 8601 1984, Majernik 2021]:

- for machines with cold chamber, the ratio SG : SSR is 1 :1.3 to 1 : 1.8,
- for machines with warm chamber, the ratio SG : SSR is 1 : 1.5 to 1 : 2.

The calculation of the runner cross-section depends on the multiplicity of the molds. The main factor influencing the cross-sectional areas of runners is the branching of runners. If the runner is divided into branches, the total cross-section should be increased by 5 to 30 % after each division, in the direction from the gate to the bisquit. In the actual calculation, we proceed in such a way, that we design the cross-sections of runners gradually away from the gate [NADCA 2006, Majernik 2021, Ragan 2007].

The cross-section of the runner before opening into the gate for machines with a cold horizontal chamber is determined by the relation (8) [Majernik 2021]:

$$S_R = n * (1.3 - 1.8) * S_G \quad (8)$$

Where:

S_R – runner area [m^2],

n – number of casts (gates), into which the melt is being led from runner,

S_G – gate area [m^2].

Cross-section of branching runner is determined by relation (9) [NADCA 2006 and 2015]:

$$S_{RM} = (S_{R1} + S_{R2} + \cdots + S_{Rn}) * k \quad (9)$$

Where:

S_{RM} – runner area after merging [m^2],

S_{Rn} – area of the nth merged runner [m^2],

k – coefficient for enlarging the cross-section of runner k = 5 – 30%.

2.1.6. Determination of geometric characteristics and design of gating system parts

Connection the cast to the gating system – the gate

The gate for connecting the gating system to the cast is designed individually. Fig. 3 depicts several typical examples of the design solution for connection the gate to the cast.

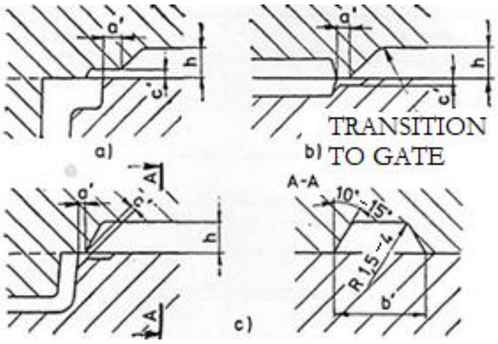

Figure 3. Possibilities of connection of cast to the gate [CSN 22 8601 1984, Majernik 2021]

Tab. 9 states the recommended geometric characteristics for connection of the cast to the gate for individual types of alloys [CSN 22 8601 1984].

Table 9. Recommended dimension values of the gate

Alloy	Dimensions of gate connection, mm	
	a´	b´
Zn	0.00 - 1.50	0.35 - 1.20
Al	0.00 - 3.00	0.70 - 2.50
Mg	2.00 - 3.00	0.60 - 2.00
Cu	2.50 - 3.00	0.80 - 3.00

Connection of the cast with cylindrical surface to the gating system – the gate

The shape of the gate must exactly copy the shape of cylindrical surface, and thus the radius of its curvature must be identical to the curvature of the surface to which we want to connect it. If the cast is of a rotational nature, its radius simultaneously tells us the curvature radius of the gate. When designing the shape of the gate in the parting plane, it is possible to proceed according to the diagram in Fig. 4 [Gaspar 2017, Majernik 2021]:

Where:
α = 30°,
β = 30°,
R – radius of the cylindrical surface [m].

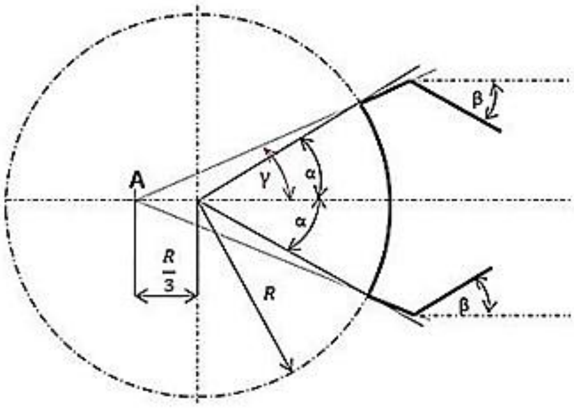

Figure 4. Diagram of the gate connection to the cylindrical surface [Majernik 2021]

The following relation can be used to determine the length of the gate a (10) [Majernik 2021]:

$$a = \frac{2.\pi.R.\alpha}{360} = \frac{2.\pi.R.60}{360} = \frac{\pi.R}{3} \quad (10)$$

Where:
a – length of the gate [m],
α = 60°,
β = 30°,
R – radius of the cylindrical surface [m].

The height of the gate b is determined from the relation (11) [Majernik 2021]:

$$b = \frac{S_G}{a} \quad (11)$$

Where:
b – height of the gate [m],
S_G – gate area [m^2],
a – length of the gate [m].

Dimensions of the runner

The cross-section of the runner is usually selected to be circular or trapezoidal. In practice, the trapezoidal shape is most often used, according to the Fig. 5, which also corresponds to Fig 3 c).

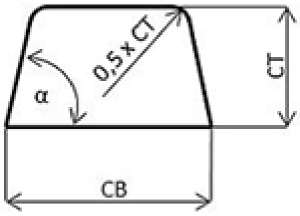

Figure 5. Possibilities of connection of cast to the gate [2021]

The dimensions of the runner can be determined according to the relation (12) [gaspar 2017]:

$$S_R = CB.CT - CT^2.tg(90^\circ - \alpha) = 2.CT^2 - CT^2.tg(90^\circ - \alpha) \Rightarrow CT = \sqrt{\frac{S_R}{2 - tg(90^\circ - \alpha)}} \quad (12)$$

Where:
SR – gate area [m2],
CT – gate height [m],
CB – gate width [m],
α – inclination angle of the runner walls [°]; selecting 75°-80°.

The runner width CB can be determined from relation (13):

$$CB = 2.CT \quad (13)$$

2.2 Cast characteristics

The numerical design of the gating system was performed on the cast of the electric motor flange according to Fig. 6. The cast is made of alloy EN AC 47100 (AlSi12Cu1(Fe)).

Figure 6. Electric motor flange cast

Tab. 6 states the basic volume and dimensional characteristics of the cast.

Table 10. Volume and weight characteristics of the cast

Quantity	Value
Alloy	EN AC 47 100 – AlSi12Cu(Fe)
Alloy density ρ, kg.m^{-3}	2650
Cast volume V_{cast}, m^3	51697.9*10^{-9}
Cast weight m_C, kg	0.136
Cast diameter, m	0.1165
Characteristic cast wall thickness h_{CH}, m	0.002

3 RESULTS

The assessment of the high pressure die casting gating system numerical design methodology with regard to the utilization of the material will be performed in the following steps:
- gating system numerical design with regard to the method of determining the filling time of mold cavity and determining the gate cross-section,
- determination of the gating system volume,
- utilization of the metal batch for one operation,
- the size of the necessary locking force of the machine.

3.1 Gating system numerical design

According to the methodology summarized in Chapter 2.1, the starting parameter for the gating system numerical design is the determination of the mold cavity filling time t. As follows from Tab. 1 for a cast with characteristic cast wall thickness of h_{CH} = 2 mm corresponds to the mold cavity filling time in the range of t = 0.02 s – 0.06 s. This interval is relatively wide. Utilizing the graph according to Fig. 1, it is possible to deter-mine the mold cavity filling time to t = 0.06 s.

According to the methodology formulated by the NADCA association, it is possible to determine the mold cavity filling time t according to the relation (1). Based on this relation, the mold cavity filling time is:

$$t = K * \left\{\frac{T_G - T_{LIK} + S * Z}{T_{LIK} - T_D}\right\} * h_{CH} = 0.029\ s$$

Where:

t – filling time [s], T_G = 660 °C, T_{LIK} = 590 °C, T_D = 200 °C, S = 20 %, Z = 4.8 °C/%, K = 34.6 s/m, h_{CH} = 0.002 m.

From the above-mentioned relations and graphs, it follows that the relevantly considered mold cavity filling time can acquire the value t = 0.029 s according the methodology of NADCA, or t = 0.06 s according to the empirically derived diagram in compliance with Fig. 1. Both values fit within the interval specified in the CSN 22 8601 standard.

According to the standard CSN 22 8601, the melt velocity in the gate for aluminium alloy cast is defined in the interval of v_G= 20 - 60 m.s^{-1}. (see Tab. 3). Therefore, the correct determination of the melt velocity in the gate requires certain experience of technologists and designers. On the basis of empirically derived graphic dependencies (see Fig. 2), it is possible to determine the gate velocity for a cast with cast wall thickness 2 mm and a diameter of 116,5 mm (equivalent to the length dimension shown in the graph) to the value of v_G=35 m.s^{-1}. In the numerical design, due to the demonstration of the mold cavity filling time impact, both values will be used.

Numerically, it is possible to determine the melt velocity in the gate in compliance with relation (2), where the melt velocity is determined as follows:

$$v_G = \frac{m_C}{\rho * t * d_p * 0.785} = 32.16\ m/s$$

Where:

v_G – velocity in the gate [m.s-1], m_C = 0.136 kg, ρ = 2650 kg.m-3, t = 0.029 s, d_p = 0.07 m, 0.785 – constant.

Both determined values of the melt velocity in the gate fit into the interval specified in the standard CSN 22 8601. Since the velocity v_G derived from the empirical graph and calculated velocity also reach close values, in the next calculation, the value of the melt velocity in the gate which was determined based on relation (2), v_G = 32.16 m.s^{-1} will be considered.

In compliance with the values listed in Tab. 4, for the characteristic cast wall thickness h_{ch} = 2 mm, with required high quality of the surface, is to determine the aggregate volume of the overflows to the value of $V_{overflows}$ = 38 % from the cast volume. That is approximately $V_{overflows}$ = 19645.202 mm^3. After conversion, the weight of overflows is equal to $m_{overflows}$ = 52 g.

The calculation of the gate cross-section will be performed in compliance with the relations given in chapter 2.1.4. According to the relation (4), the gate cross-sectional area for Variant 1 is determined as follows S_{G1}:

$$S_{G1} = \frac{G}{\rho * t * v_G} = 76.06 * 10^{-6}\ m^2$$

Where:

S_{G1} – gate area Variant 1 [m^2], G = 0.188 kg, ρ = 2650 kg.m^{-3}, v_G = 32.16 m.s^{-1}, t = 0.029 s.

According to the relation (5), the gate cross-sectional area for Variant 2 is determined as follows S_{G2}:

$$S_{G2} = \frac{G}{\rho * (k_1 * k_2 * v_t) * (k_3 * k_4 * t)} = 48.32 * 10^{-6}\ m^2$$

Where:

S_{G2} – gate area Variant 2 [m^2], G = 0.188 kg, ρ = 2650 kg.m^{-3}, v_t = 15 m.s^{-1}, t = 0.029 s, k_1 = 1.25, k_2 = 2, k_3 = 0.9, k_4 = 1.5, see Tab. 5 - Tab. 8.

According to the relation (6), the gate cross-sectional area for Variant 3 is determined as follows S_{G3}:

$$S_{G3} = 0.1 * \sqrt{V * e} = 119.5 * 10^{-6}\ m^2$$

Where:

S_{G3} – gate area Variant 3[m^2], 0.1 – constant in compliance with CSN 22 8601, V = 71343.1*10-9 m^3, e = 0.002 m.

According to the relation (7), the gate cross-sectional area for Variant 4 is determined as follows S_{G4}:

$$S_{G4} = 0.016 * (V)^{0.745} = 66.05 * 10^{-6}\ m^2$$

Where:

S_{G4} – gate area Variant 4 [m^2], 0.016 – constant in compliance with CSN 22 8601, V = 71343.1*10-9 m^3, 0.745 – exponent in compliance with CSN 22 8601.

To determine the gate cross-section for Variant 5, relation (5) will be used, while the value t will be at t = 0.06 s, which follows the empirically derived graph in compliance with Fig. 1.

$$S_{G5} = \frac{G}{\rho * (k_1 * k_2 * v_t) * (k_3 * k_4 * t)} = 35.03 * 10^{-6}\ m^2$$

Where:

S_{G5} – gate area Variant 5 [m^2], G = 0.188 kg, ρ = 2650 kg.m^{-3}, v_t = 15 m.s^{-1}, t = 0.06 s, k_1 = 1.25, k_2 = 2, k_3 = 0.9, k_4 = 1.5, see Tab. 5 - Tab. 8.

It will be in compliance with the methodology stated in chapter 2.1.6 to determine the dimensions of the gate. The relation (10) will be used for the gate length, and thus the gate connection to the cast with cylindrical surface:

$$a = \frac{2.\pi.R.\alpha}{360} = \frac{2.\pi.R.60}{360} = \frac{\pi.R}{3} = 60.968 * 10^{-3} m$$

Where:

a – length of the gate [m], α = 60°, β = 30°, R = 0.05825 m.

The length of the gate is constant for all variants of the gate cross-section calculation. The variable parameter determining the gate cross-section is its height b. If the values S_{G1} – S_{G5} and the value a, are substituted into the relation (11), it is possible to determine the dimensions of the gate as listed in Tab. 11.

When comparing the resulting values of the height of the gate b with permissible values in compliance with the standard CSN 22 8601 [CSN 22 8601 1984] (see Tab. 9), it is clear that the height of the gate for Variant 5, b_5 = 0.57 mm, is outside the interval determined by the standard. The gate height b range for al-based casts is determined by the standard for values of b = 0.7 – 2.5 mm. in order to demonstrate the possible impacts on the monitored properties, this value will also be considered in the following calculation and solution. The calculation of the gate cross-section will be performed in compliance with relations stated in chapter 2.1.5. As stated, for machines with a horizontal cold chamber, the ratio of the cross-section of secondary runner (before passing to the gate) to the cross-section of the gate is determined by the ratio S_G : S_{SR} is 1 :1.3 to 1:1.8.

Table 11. Dimensions of the gate

	Area of the Gate S_G	Length of the Gate a	Height of the Gate b, mm
Variant 1	S_{G1} = 76.06 mm²		b_1 = 1.25 mm
Variant 2	S_{G2} = 48.32 mm²		b_2 = 0.79 mm
Variant 3	S_{G3} = 119.50 mm²	a = 60.968 mm	b_3 = 1.96 mm
Variant 4	S_{G4} = 66.05 mm²		b_4 = 1.08 mm
Variant 5	S_{G5} = 35.03 mm²		b_5 = 0.57 mm

In order to maintain the constancy of the calculation for all variants of the gating system design calculation, the S_G : S_{SR} ratio was selected to be 1.5. If relation (8) is considered, it is possible to calculate the values of the secondary runner's cross-section as stated in Tab. 12.

In the event that the main runner is divided into a secondary one, we consider a 5 – 30 % increase in the cross-sectional area towards the bisquit. A 10 % increase in the cross-section is considered for the given cast. The cross-section of the main runner for individual variants is determined in compliance with the relation (9) and defined in Tab. 12.

Table 12. Cross-section of the runners

	Cross-sectional area of the secondary runner	Cross-sectional area of the main runner
Variant 1	S_{SR1} = 228.18 mm²	S_{MR1} = 501.99 mm²
Variant 2	S_{SR2} = 144.96 mm²	S_{MR2} = 318.91 mm²
Variant 3	S_{SR3} = 358.50 mm²	S_{MR3} = 788.70 mm²
Variant 4	S_{SR4} = 198.15 mm²	S_{MR4} = 435.92 mm²
Variant 5	S_{SR5} = 105.09 mm²	S_{MR5} = 231.20 mm²

When considering the trapezoidal cross-section of the secondary runners, their dimensions can be deter-mined in compliance with the relations (12) and (13). The geometric dimensions of the runners according to Fig. 5. Are listed in Tab. 13.
Since the gating system design methodology is being assessed, the length of the runners, their mutual connection as well as the overall gating system shape remained identical to the initial gating system utilized in real industrial production, at the values of l_{MR} = 264 mm and l_{SR}= 280 mm. Fig. 7 depicts the basic shape of the gating system and the distribution of casts, including the filling chamber.

Table 13. Cross-section of the runners

	Variant 1	Variant 2	Variant 3	Variant 4	Variant 5
Secondary runner					
CT	11.48 mm	9.15 mm	14.39 mm	10.69 mm	7.79 mm
CB	22.96 mm	18.30 mm	28.78 mm	31.38 mm	15.58 mm
Main runner					
CT	11.48 mm	9.15 mm	14.39 mm	10.69 mm	7.79 mm
CB	46.80 mm	37.30 mm	58.66 mm	43.64 mm	31.80 mm
Curvature radius, r	6 mm	4.5 mm	7 mm	5 mm	4 mm
Walls inclination angle, α	75°	75°	75°	75°	75°

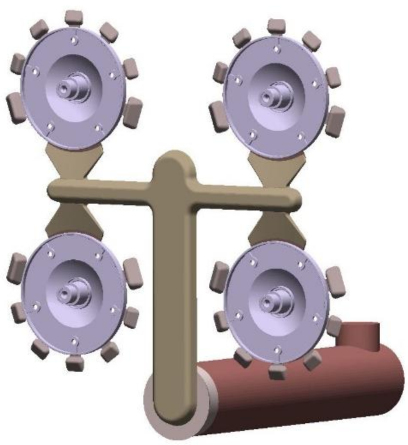

Figure 7. Basic shape of the gating system

3.2 Assessment of material utilization for individual variants of numerical design

According to above calculations and the data presented in Tab. 11, Tab. 12, Tab. 13 and Fig. 7, it is evident that the use of different variants of the numerical solution for specific cast type gating system design also entails different requirements for material utilization. Tab. 14 states the weight and volume characteristics of the individual gating systems variants, as well as the calculation of the difference between raw and crude casts, i.e. determining the utilization of the batch for one operation.
As the volume of the gating system increases, the percentage of the filling of a chamber also increases. It has been demonstrated that with the higher filling of the chamber, the porosity of casts decreases and the melt, when passing through the gating

system, shows more favorable temperature characteristics when filling the mold cavity [Hsu 2013, Bi 2015].

Table 14. Utilization of the metal batch for one operation

		Variant 1	Variant 2	Variant 3	Variant 4	Variant 5
Crude cast	Volume	$206.80*10^{-6}$ m^3				
	Weight	0.544 kg				
Raw cast	Volume	$554.63*10^{-6}$ m^3	$409.12*10^{-6}$ m^3	$656.11*10^{-6}$ m^3	$536.92*10^{-6}$ m^3	$456.68*10^{-6}$ m^3
	Weight	1.470 kg	1.299 kg	1.739 kg	1.423 kg	1.210 kg
Utilization		37 %	42 %	31 %	38 %	45 %

In compliance with the volume characteristics for the raw cast listed in Tab. 14, the percentage values of the filling of the chamber are listed in Tab. 15.

Table 15. Percentual proportion of filling of the chamber

	Variant 1	Variant 2	Variant 3	Variant 4	Variant 5
Chamber length	0.35 m				
Piston diameter	0.07 m				
Chamber volume	$1346.275*10^{-6}$ m^3				
Filling the chamber	41.20 %	36.41 %	48.74 %	39.88 %	33.92 %

3.3 Determination of necessary locking force of the machine

As evident, in the compliance with the different calculation of the gate, not only the cross-section of the runners, but also their geometry is changing. The exact values of the geometric dimensions of individual runner variants are stated in Tab. 13. With the variable dimension CB – the runner width, the projection of the gating system area to the parting plane of the mold also changes, which naturally causes a change in the size of re-quired minimum locking force of the machine. The size of the locking force of the machine can be determined from relations (14) and (15) [Majernik 2021, Ragan 2007]:

$$F_L \geq k * F_O \qquad (14)$$

Where:
FL – locking force [N],
FO – opening force [N],
k – coefficient of safety; minimum selected k = 1.1 (10%)

$$F_O = S_{Cmax} * p_{max} \qquad (15)$$

Where:
FO – opening force [N],
SCmax – maximum gating system area projection in parting plane, including the biscuit, runners and overflows [m2],
pmax – maximum pressure on melt (holding pressure) [Pa].
Table 16 depicts the minimum locking force values for individual calculation variants.

Table 16. Determination of the necessary locking force

	Variant 1	Variant 2	Variant 3	Variant 4	Variant 5
Parting plane area projection S_{Cmax}, cm^2	771.71	746.90	797.48	757.98	726.63
Holding pressure p_{max}, MPa	25				
Opening force F_O, kN	1929.27	1867.25	1993.71	1894.95	1816.57
Coefficient of safety k	1.2				
Designed locking force F_L, kN	2315.12	2240.70	2392.45	2273.94	2179.88

4 DISCUSISION

The submitted contribution is focused on the suitability assessment of the gating system design calculation methods for a specific low-weight silumin based cast produced via the high-pressure die casting. The chara-teristic dimensions of the cast, cast weight, overflow volume, filling time of mold cavity and the velocity of the melt in the gate are determined as the default parameters for the gating system design and the calculation solution of the geometry of its parts.

The characteristic dimensions of the cast are given by the drawing documentation for the crude cast. The cast weight, or a set of casts, based on the selection of the four-bed mold and the drawing of the crude cast, is determined by the value of 0.544 kg. According to the Tab. 4, the overflow weight for entire set of casts is determined by the value of 0.208 kg. These parameters, based on the drawing documentation for a specific type of cast, are more or less constantly determined.

The filling time of mold cavity can be determined based on three variants. The first variant is the determination of the filling time of mold cavity in accordance with CSN 22 8601. In Tab. 1, which is created in compliance with the above-mentioned standard, for a cast with characteristic wall thickness of 2 mm, it is possible to select the filling time of mold cavity in the interval of values 0.02 – 0.06 s. Without many years of experience in the field of high-pressure die casting and design of gating systems, the selection of the correct filling time of mold cavity based on Tab. 1 is impossible. Therefore, to determine the filling time of mold cavity for the calculation of gating system, the calculated values in compliance with the relation – (1) and according to the empirically derived diagram in Fig. 1 were selected. In compliance with the diagram on Fig. 1, the filling time of mold cavity is calculated at the value t = 0.06 s. According to NADCA association conceived methodology and relation (1), the filling time of mold cavity is calculated at the value t = 0.029 s. The calculation according to relation (1) takes into account the temperature characteristics of the melt and mold, the interaction between the melt and mold, and also the crystallization within the melt. During the casting cycle, the priority value for calculation of gating system design was considered the value t = 0.029 s. The filling time of mold cavity according to the diagram on Fig. 1 was used in one variant of calculation demonstratively, to verify the possible impacts on the calculation and qualitative indicators.

The velocity of the melt in the gate can be determined based on the empirically derived diagram on Fig. 2. Based on the diagram, it is possible to determine the velocity of the melt in the gate for a cast with a characteristic wall thickness of 2 mm and length of 116.5 mm to the value v_G = 35 ms^{-1}. A more accurate possibility to determine the velocity of the melt in the gate is in compliance with relation (2), according to which v_G = 32.16 ms^{-1}. Since both values are close to each other, the value v_G = 32.16 ms^{-1} was considered for the calculation of the gating system design.

The calculation of the gating system was performed in accordance with the methodology presented in Chapter 1. The first step, on which the entire calculation of gating system design is based, was the determination of the gate cross-section S_G. The values t = 0.029 s and v_G = 32.16 ms^{-1} were selected for the Variant 1 – Variant 4 calculation (in compliance with relations (4) – (7)). For the Variant 5 calculation, as mentioned above, a demonstrative value of t = 0.06 s was used while maintaining v_G = 32.16 ms^{-1}. The result of the calculation determined the cross-section values of the runners and their geometry, as stated in Tab. 11. Variant 5, in which the value for the filling time of the mold cavity was used t = 0.06 s, is showing the height of the gate b5 = 0.57 mm, which is outside the recommended range of height of the gate for aluminium alloy casts determined by the standard CSN 22 8601 (the standard determines the height of the gate range to b = 0.7 – 2.5 mm). Despite the exclusion given by this standard for the Variant 5 calculation of the relevant dimensions of the gate, the calculation for the Variant 5 gating system was still performed. It was determined that the cross-section of the gate, which is decisive for further calculations, decreases in the successive series of Variant 3 (SG3= 119.5 mm2) → Variant 1 (SG1 = 76.06 mm2) → Variant 4 (SG4 = 66.05 mm2) → Variant 2 (SG2 = 48.32 mm2) → Variant 5 (SG5 = 35.03 mm2). Based on dimensional, weight and volume characteristics of individual variants of gating system solution, the suitability of the design was assessed through the technological parameters – the size of the locking force and the proportion of the filling of the chamber and the economic indicators – the utilization of the metal batch for one operation.

As can be seen from the calculation of the individual cross-sectional and dimensional characteristics, as the cross-section of the gate S_G decreases, the cross-sections of the runners S_{SR}/S_{MR} also decrease, which also decreases the volume of entire gating system and thus the size of metal batch per operation, as stated in Tab. 14. Thus, while maintaining the constant weight of the crude cast m_{CC} = 0.544 kg, with a decrease in the amount of metal per operation, the utilization of the metal per operation increases. On the other hand, with reduction of the metal batch per operation, the proportion of the filling of the chamber decreases, as stated in Tab. 15. In Fig. 8 are mutually compared indicators of the utilization of the metal batch for one operation and the proportion of the filling of the chamber expressed in percentages.

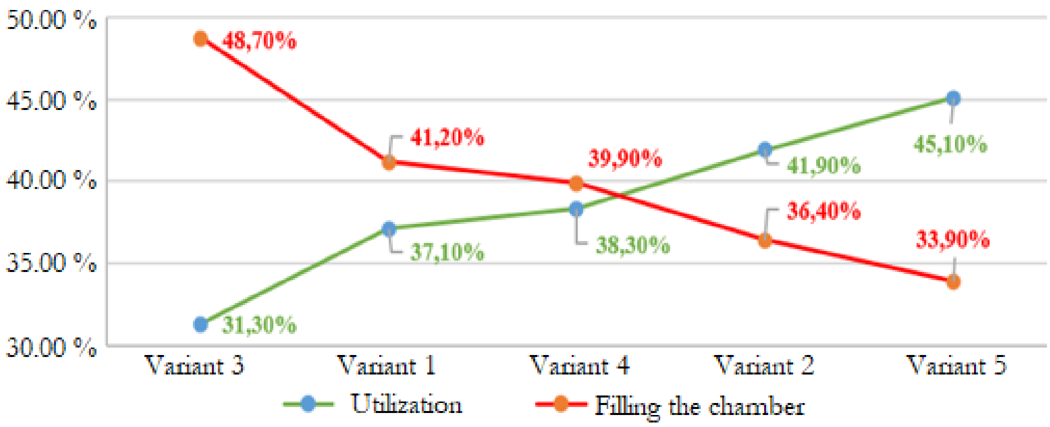

Figure 8. Comparison of the metal batch utilization and the filling of the chamber

If the utilization of the metal batch for one operation is considered as an economic indicator and the filling of the chamber as a technological indicator, theoretically speaking, the intersection point of both curves is the optimal solution for technological and economical production. In publications [Tsu 2013, Bi 2015], it is stated that with a decreasing of the metal batch per operation, and thus a decrease in the proportion of the filling of the chamber, the proportion of porosity in the casts increases. Thus, it is possible to consider that the proportion of gas entrapment in the volume of the cast will also increase as the batch of metal per operation decreases. The validity of this statement for the numerical designs of gating systems performed in this article will be verified in the following works. It is assumed that the entrapment of gases with the melt and its distribution in the cast volume will be controlled by the characteristics of the flow, not primarily by the size of the metal batch per operation.

The change in the dimensions of the gating system is also reflected in the calculation of the minimum and subsequently necessary locking force of the machine. As stated in Tab. 16, as the cross-section of the gate decreases, the dimensions of the gating system also decrease and, dependent on them, the projection of the cast/gating system area into the parting plane of the mold. The graphic representation of the change in the locking force depending on the change in the projection of the gating system are is depicted in Fig. 9. According to the figure, it is clear that with Variant 3, the stress on the machine frame and mold will be the highest from the derived locking force. If the difference between the minimum and maximum designed locking force will be considered, the difference is ΔF_L = 230.28 kN. With regard to sizes of industrially used high-pressure die casting machines, the size of the necessary designed force can be neglected as a parameter for assessing the suitability of the gating system design, or be considered to minimal extent.

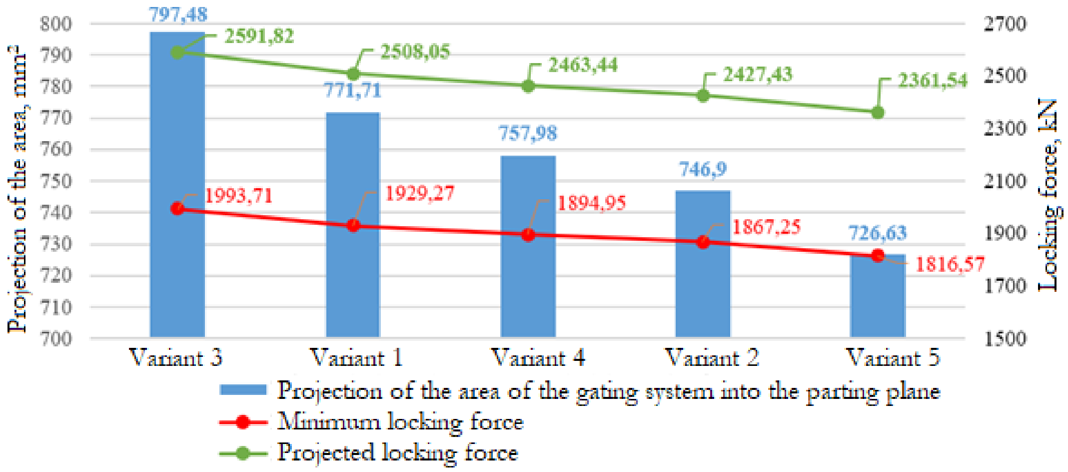

Figure 9. Change of the locking force depending on the projection of the gating system area into the parting plane of the mold

5 CONCLUSIONS

The submitted contribution is aimed at the assessment of the suitability of the gating system computational design method for a specific type of low-weight silumin based cast produced by high-pressure die casting. In accordance with the performed calculations, weight and volume characteristics of the designed gating systems, it is possible to draw the following conclusions:

- when determining the filling time of the mold cavity t, for low-weight casts, it is advantageous to determine this time based on the mathematically derived formulation in compliance with the relation (1) compared to the empirically derived diagram in Fig. 1. During the subsequent calculation of the cross-section of the gate S_G and the determination of its dimensions, the height of the gate b is outside the recommended values interval;
- determination of the melt velocity in the gate v_G is possible for low-weight casts and can be selected based on the mathematical formulation in compliance with the relation (2) as well as from the empirically derived diagram in Fig. 2. The differences between the determined values are minimal and can be used in the calculation without enormously influencing the dimensions of the gating system;
- the size of the gate cross-section S_G also affects the cross-section dimensions of the runners S_{SR} and S_{MR} (Tab. 12), which also affects the dimensions of the runners (Tab. 13);
- as the dimensions of the runners increase, the utilization of the metal batch for one operation also in-creases, which increases the economy of the production (Tab. 14). On the other hand, the proportion of the filling of the chamber increases (Tab. 15), which from technological view has a favourable effect on the gas entrapment by the melt and their transport into the volume of the cast. When comparing these assessed parameters (Fig. 8), the most advantageous calculation variants are Variant 1 (calculation in compliance with relation (4)) and Variant 4 (calculation in compliance with relation (7));
- with regard to the size of the locking force of the machine (Tab. 16), the increase in the projection of the gating system area into the parting plane of the machine is present (depending on the calculation variant), and thus also the change of the minimum or projected locking force is minimal (Fig. 9), and irrelevant.

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