Optimization of the Runner Numerical Design Dimensions using the Simulation Program

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The proper design of the gating system including the tempering and venting of the mold significantly influences the final quality of the casting and economize the costs of the foundries. The initial numerical design of the gating system is often sufficient for creating of the documentation for the mold design, but without the practical experience of the designer, it does not reveal the hidden problem emerging from the melt flow through the gating system as well as the temperature and gas mode of the mold.The contribution is dedicated to the optimization of the runner dimensions determined by the numerical calculation. The theoretical part presents the methodology, based on which the gating system was designed for a particular type of the pressure casting. The experimental part is dedicated to the influence of the cross sectional area of the runner on the change of the melt temperature before entering the ingate. It was assumed that the larger runner cross section gives the melt greater volume and heat capacity and thus the melt enters the ingate with the higher temperature. The obtained temperature results are then compared witht he melt flow rate values, based on which an optimal sulotion for the runner design dimensions is determined.

Keywords: High Pressure Die Casting, Runner, Construction, Technological Parameters

1 Introduction

The principles for gating system design are compiled in the Czech Republic standard ČSN 22 8601. The gating system dimensions are based on the dimensional and volumetric parameters of the casting, on the basis of which the gate cross section is determined. The calculation of the cross sectional area of the runners is based on the gate area. This standard specifies the initial parameters for determination of the dimensions of the gate: the filling time of mold cavity and the gate melt velocity. The minimum ratio of the gate area and the cross section of the channel before entering the ingate is shown for the design of the gating channels. The recommended parameter values are stated at the permissible intervals delimited by the maximum and minimum permissible values. [1] The possibility of correct selection is limited by the constructor´s experience and thus implements the risk of error calculation. The error created by selection of the input parameters in the design by selecting from the prescribed interval is eliminated by the calculation formulated by J. F. Wallace and E. A. Herman in the Gating Manual, issued under the auspices of NADCA. [2] In the monography Influence of Structure Adjustment of Gating System of Casting Mold upon the Quality of Die Cast (Gašpár, 2017, Lüdenscheid: RAM - Verlag), authors drew on the above-mentioned methods of designing the gating systems and established the design methodology according to which the gating system for casting has been designed and put under the investigation. [3]

The results presented int he contribution were based on the design solution of the gating sytem for casting of the gear pump thrust face presented on Fig. 1.

Fig. 1 *Thrust face of the gear pump*

The design of the gating system was realized based on the methodology described in the monography [3] according to Gašpar et al. The numerical design, considered as a referenced, was subsequently modified by reducing the cross section of the runners in order to find out the most advantageous solution of the ratio between the temperature capacity inside the melt volume and the melt flow rate. NovaFlow&Solid simulations were performed on the individual equivalents of the solution.

2 Methodology of the gating system design

The first parameter required to determine the gate area is the filling time of the mold cavity. The best method of the calculation was the NADCA method. The empirically derived formula i sused to determine the filling time of mold cavity:

$$t = K.\left\{\frac{T_Z - T_{LIK} + S.Z}{T_{LIK} - T_f}\right\}.h_{ch} \qquad (1)$$

Where:
t – filling time [s]
TZ – melt temperature in the gate [°C],
TLIK – temperature of the liquidus [°C],
Tf – mold temperature [°C],
S – permissible percent of the melt solidification at the end of the mold cavity filling [%],
Z – the particle conversion factor related to the solidification range [°C/%],
K – the empirically derived constant associated with the conductivity of the mold [s/m],
hch – characteristic thickness of the casting wall [m], hch = 0,002m .

Part of the equation in brackets expresses the temperature dependencies and processes within the mold.

The constant *K* acquires the values:
- 0,0312 s/mm between the AISI P-20 steel (preliminary hardened nitrated steel for plastic injection molds) and zinc alloys,
- 0,0252 s/mm between the AISI H-13 steel (steel and chromium alloys) and the AISI H-21 steel (alloys of steel, chromium and tungsten) and magnesium alloys,
- 0,0346 s/mm between the AISI H-13 and AISI H-21 steels, aluminium and brass alloys,
- 0,0124 s/mm between tungsten and magnesium, zinc, aluminum and brass alloys.

The following ***Tab. 1*** shows the permissible values for solidification depending on the thickness of the wall.

Tab. 1 *The permissible values for solidification of the material depending on the thickness of the wall*

Thickness of the wall, mm	Permissible values for material solidification *S* [%]		
	Aluminum	Magnesium	Zinc
< 0,8	5	10	5 - 15
0,8 - 1,25	5 - 25	5 - 15	10 - 20
1,25 - 2	15 - 35	10 - 25	15 - 30
2 - 3	20 -50	20 - 35	20 - 35

Constant Z acquires values:
4,8 °C/% for ASTM 360, 380 a 384 aluminum alloys, all subeutectonic alloys of AlSi (Cu/Mg) containing less than 12% of silicon,
5,9 °C/% for ASTM 390 aluminum alloys, aboveeutectonic alloys of 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.

If the mold cavity filling time is know, based on the character of the alloy and the diameter of the plunger, it is possible to determine the melt velocity in the ingate according to:

$$v_z = \frac{m_O}{\rho . t . d_p .0,785} \qquad (2)$$

Where:
v_z – velocity of the melt flow in ingate [m.s^{-1}]
ρ – alooy density [kg.m^{-3}]
d_p – diameter of the filling chamber of the machinepriemer plniacej komory stroja [m],
0,785 – constant

The gate area of Variant 1 was determined according to:

$$S_Z = \frac{G}{\rho . t . v_z} = 0,7606 cm^2 \qquad (3)$$

Where:
G – the sum of the casting weight and the flow rates

Once the basic starting parameters have been determined, it is possible to determine the dimensional characteristics of the ingate. The width of the ingate is dependent on the radius of the casting and is determined according to the method of projection of the ingate connection to the casting according to:

$$a = \frac{2 . \pi . R . \alpha}{360} = \frac{2 . \pi . R . 60}{360} = \frac{\pi . R}{3} \qquad (4)$$

a – ingate width [m]
α – the angle defining the length of the ingate [°], constantly acquires the value *α* = 60°
R – the radius of the cylindrical surface of the casting to which the ingate is attached [m].

Ingate height is determined according to:

$$b = \frac{S_Z}{a} \qquad (5)$$

The cross section of the runner has the shape of a trapezoid with a wall inclination of 10°-15° (***Fig. 2***). The ratio of height and average width of the channel should be within the ratio 1:1 to 1:3. usually its 1:2.

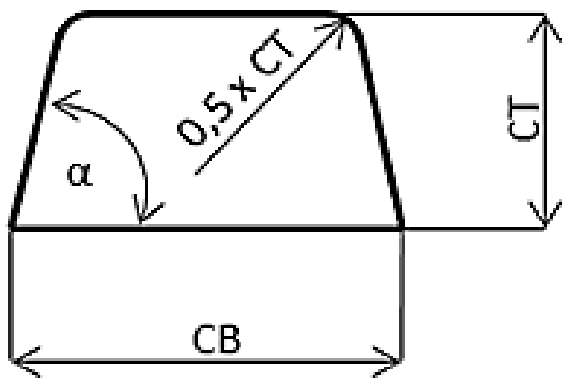

Fig. 2 *Cross section of runner [3]*

The calculation of the runner depends on the multiplicity of the mold. The influence on the runner

cross section has mostly the runner branching, while it should be valid that if the runner is split by branching, its overall cross section should be increased by 5 to 30 % after each split from the gate to the bisquit.

The calculation itself is done by designing the diameters of the runners in the opposite direction than the ingate.

The cross section of the runner is determined according to:

$$S_K = n.2.S_Z \tag{6}$$

Where:

n – the number of the castings into which the melt is led through the runner.

Due to recommended ratio of the ingate and the runner surface it is possible to neglect the roundness of the runner and for the runner height is defined the formula:

$$S_K = CB.CT - CT^2.\,tg(90^\circ - \alpha) = 2.CT^2 - CT^2.tg(90^\circ - \alpha) \Rightarrow CT = \sqrt{\frac{S_K}{2 - tg(90^\circ - \alpha)}} \tag{7}$$

Where:

α – angle of the runner walls gradient

Depending on the defined runner height: The runner width:

$$CB = 2.CT \tag{8}$$

The branching runner surface can be determine according to:

$$S_{KZ} = \left(S_{K1} + S_{K2} + ... + S_{KN}\right).k \tag{9}$$

Where:

S_{KZ} – the runner area after the unification,

S_{KN} – the area of n-th joint runner,

k – coefficient of the runner cross section increase (5 – 30%). [3]

3 Characteristics of the gating system and measuring points

Based on the above described methodology of the gating system design, a reference gating system was constructed. In ***Tab. 2*** the basic dimensional characteristics of proposed gating system are stated.

Tab. 2 *Dimensional characteristics of gating system*

MAIN RUNNER		**ADJOINING RUNNER**	
Parameter	Value	Parameter	Value
Cross section area / S_K	831.9 ^ 10^{-6} m^2	Cross section area / S_{KV}	440 ^ 10^{-6} m^2
Height / CT	15.94 ^ 10^{-3} m	Height / CT	15.94 ^ 10^{-3} m
Width / CB	56.46 ^ 10^{-3} m	Width / CB	31.88 ^ 10^{-3} m
Length / l	100 ^ 10^{-3} m	Length / l_V	593.11 ^ 10^{-3} m
Angle of the walls / α	75°	Angle of the walls / α	75°
Roundness intensity	8 ^ 10^{-3} m	Roundness intensity	8 ^ 10^{-3} m
INGATE			
Gate area / S_Z		54.96 ^ 10^{-6} m^2	
Gate length / a		19.82 ^ 10^{-3} m	
Gate height / b		2.77 ^ 10^{-3} m	

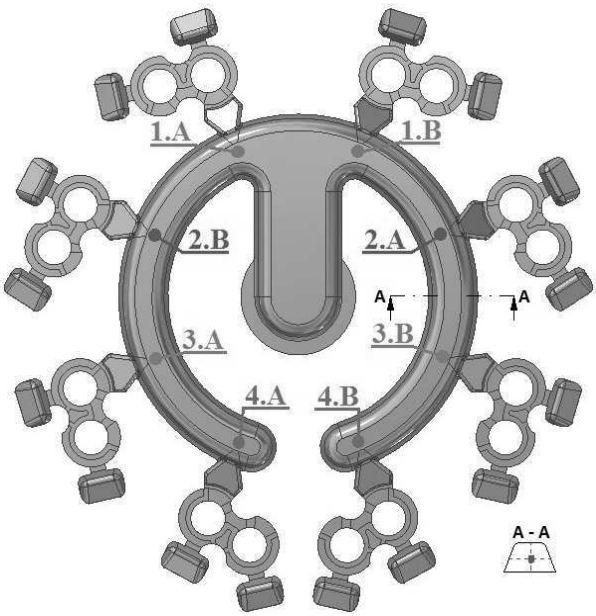

Fig. 3 *Measuring points in the gate system*

In order to ensure the sufficient range of measuring points in the runner, thethe octuple gating system with a central arrangement was designed for testing (Fig. 3). Fig. 3 depics the layout of the measuring pooints in the runner.

The measurement was carried out at the center of the runners (Fig. 2, section A-A), on the nominal diameter of the runner. The location of the measuring points against the gates was chosen with respect to knowledge of the state and temperature of the melt before entering the mold cavity. The temperature values in the individual measuring points were monitored. Since the two measuring points belong to one average length of the melt flow, the average of the values measured at these locations was evaluated. [5]

In order to ensure the sufficient range of results, the reference gating system was modified so that the simulation tests were carried out on the seven types of the runner widths. In ***Tab. 3***, the dimensions of the runners of the modified gating systems and the average lengths of the melt flow at the individual measuring points are shown.

Tab. 3 *Examined parameters of gating system*

RUNNER DIMENSIONS				
		Runner area *S* [mm²]	Runner width *CB* [mm]	Runner height *CT* [mm]
1. VK440 Reference	VK	**440.098**	**31.88**	**15.94**
	HK	**831.9**	**56.46**	**15.94**
2. VK420	VK	**420**	**30.62**	**15.94**
	HK	**792.45**	**53.98**	**15.94**
3. VK400	VK	**400**	**29.36**	**15.94**
	HK	**754.72**	**51.62**	**15.94**
4. VK380	VK	**380**	**28.10**	**15.94**
	HK	**716.98**	**49.24**	**15.94**
5. VK360	VK	**360**	**26.84**	**15.94**
	HK	**679.25**	**46.88**	**15.94**
6. VK340	VK	**340**	**25.58**	**15.94**
	HK	**641.51**	**44.52**	**15.94**
7. VK320	VK	**320**	**24.35**	**15.94**
	HK	**603.77**	**42.15**	**15.94**

AVERAGE MELT FLOW LENGTH l_S [mm]				
Measuring point	l_{S1}	l_{S2}	l_{S3}	l_{S4}
1.A / 1.B	**139.25**	----------	----------	----------
2.A / 2.B	----------	**217.75**	----------	----------
3.A / 3.B	----------	----------	**296.25**	----------
4.A / 4.B	----------	----------	----------	**374.75**

*VK – adjoining runner
*HK – main runner

4 Analysis of the melt temperature change

Because of the relevance of the results, the setting of technological parameters during the casting cycle for all models was maintained at a constant level. The temperature of the melt in the pressing chamber was maintained at T_T = 610°C, the mold temperature was T_f = 200°C and in the runned, the constant mass flow was set on Q_m = 55,446kg.s^{-1}. In practice, the melt temperature by entering the mold cavity should be at least 10 to 20°C higher than the temperature at which the melt begins to crystallize. If the hot mel tis cast into a cold mold which has been insufficiently insulated with a suitable lubricant, the surface layers of the mold will be heavily stressed and the mold will wear out sooner. The low melt temperature on the casting is manifested by the formation of cold joints, weldings and map surfaces. For this reason, the temperature of the individual measuring points was monitored. In ***Tab. 4*** and ***Tab. 5***, the melt temperature values in the individual runners is shown. The temperature of the firstly oxidized face of the mel tis evaluated at the first contact with the measuring point and the melt temperature at the end of the filling.

Tab. 4 *The temperature of the melt flow front*

TEMPERATURE OF THE MELT FLOW FACE T_{fm} [°C]							
	cross section of runner						
Point	**VK440**	**VK420**	**VK400**	**VK380**	**VK360**	**VK340**	**VK320**
1. / T_1	599.17	587.665	581.925	587.975	592.18	587.07	588.375
2. / T_2	583.77	592.895	587.135	584.83	584.975	583.73	585.275
3. / T_3	567.115	572.48	577.015	568.19	567.525	559.83	566.925
4. / T_4	572.255	575.08	572.265	575.93	581.025	580.75	580.24

Tab. 5 *Temperature of the melt at the end of the filling*

TEMPERATURE OF THE MELT AT THE END OF THE FILLING T_{ef} [°C]							
	cross section of runner						
Point	**VK440**	**VK420**	**VK400**	**VK380**	**VK360**	**VK340**	**VK320**
1. / T_1	604.99	605.065	605.99	605.222	605.52	606.275	605.32
2. / T_2	604.03	603.975	603.695	604.3	604.37	604.19	604.045
3. / T_3	597.045	596.87	599.26	597.665	599.425	599.335	599.26
4. / T_4	582.35	584.06	585.575	585.855	587.225	586.155	585.665

Prior to the simulation, it was assumed that a larger cross section of the runner gives the melt greater volume and heat capacity and thus the melt enters the gate even at a higher temperature. This premise was disproved by the simulation. It has been shown that the highest temperatures at the measuring points were shown by the

variation of the gating system No.5, designated as a VK360.

Alloy EN AC 47100 was selected for casting, which liquidus temperature is according to the material list T_{liq} = 590°C. The simulations showed, that the condition of value of minumum melt overheat while entering the mold cavity 10 to 20°C above the liquidus is reached only at the runner lengths l_{S1} and l_{S2}. For a better visualisation of the temperature change during the filling of the mold cavity, the graph was constructed (***Fig. 4***). The graph shows the development of the temperature in runner No. 5 – VK360, which evinced the highest temperatures in the measuring points, and the temperatures in the runners No.1 – VK440 and No.7 – VK320, which are characterized by boundry values of the runner cross section. The development of the temperatures are plotted at measuring points 1 and 4.

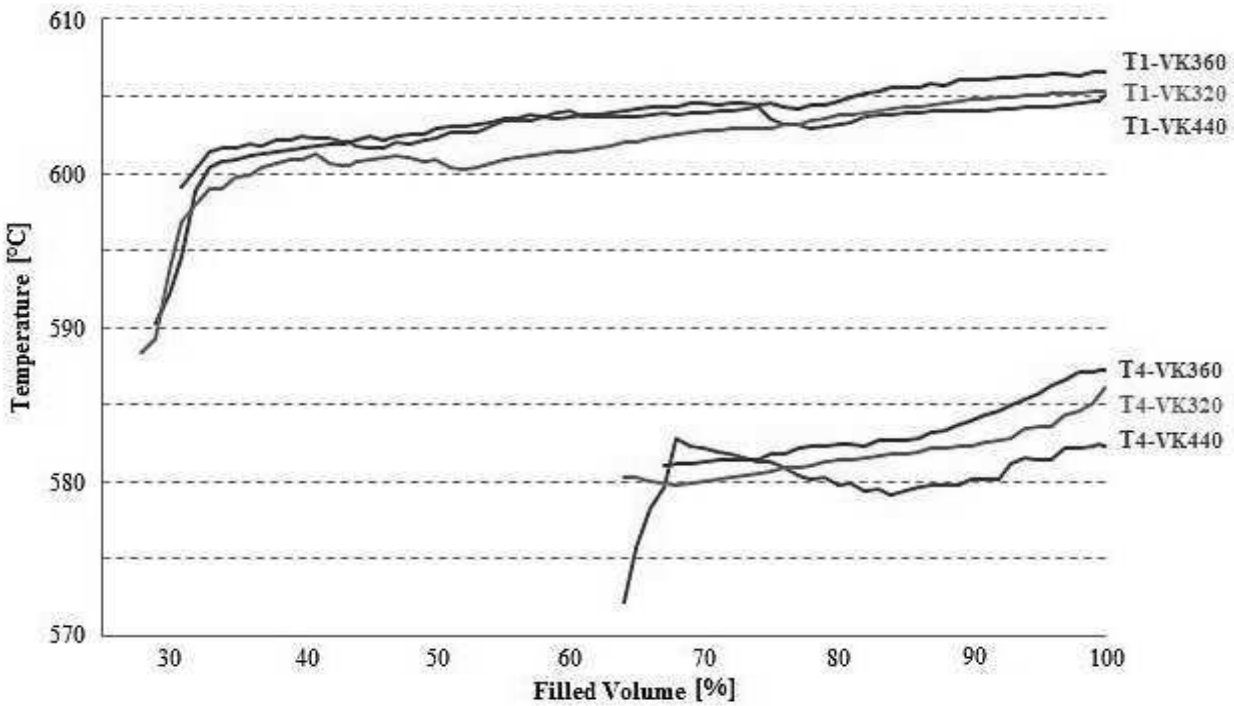

Fig. 4 *Melt temperature during the filling*

It should be noted that the melt flow front is formed by a firstly solidificated layer of oxidized metal, which after the transition through the cast is being retained by the owerflows. The measuring point is after the transition supplied by a new melt from the filling chamber and thus carries a higher temperature. The value of the melt flow face is therefore indicative of the temperature range in which the mel tis present during the filling.

5 Analysis of the melt flow velocity in the runner

Since the experiments describing the temperature states of the melt during the transition through runners disproved the initial assumtion of higher thermal capacity, the authors focused on the melt velocity assessment and the associated filling time.

In order to ensure the results of velocities with the assumtion of laminar flow, the measuring points 1.A/1.B and 4.A/4.B were excluded because due to the geometry of the gating system occured the turbulences and swirling of the melt. Velocities in the points 2.A/2.B and 3.A/3.B were considered only in the state in which the melt filled 100% of the cross section of the runner in the measurement point. In ***Tab. 6*** the velocity values in the runner are stated.

Tab. 6 *The runner melt velocity values*

MELT VELOCITY IN RUNNER v_R [m.s^{-1}]			
Runner no.	**MEASURING POINT**		**Mean**
	2	**3**	
1. VK440	27.25	23.74	25.50
5. VK360	31.01	25.12	28.06
7. VK320	32,04	26,11	29.07

With the decreasing cross section of the runner while maintaining a constant mass flow rate Q_m the melt flow velocity in the runner v_R increases, thereby shortening the filling time of the mold cavity. ***Tab. 7*** shows the filling times of the mold cavity of individual gating systems acquired by simulation.

Tab. 7 *Mold cavity filling time values*

MOLD CAVITY FILLING TIME	
Runner no.	**Filling Time *t* [s]**
1. VK440	0.029
2. VK420	0.028
3. VK400	0.028
4. VK380	0.027
5. VK360	0.026
6. VK340	0.026
7. VK320	0.025

6 Analysis of results

As demonstrated, the most advantageous temperature ratios of the melt before entering the gate were reached by the gating system No. 5 VK360, with dimensions of the runners according to the ***Tab. 3***.

The assumption that the best temperature characteristics will be achieved by the reference gating system No. 1 VK440 has been disproved. The explanation could be in the reference on the melt flow velocity in runner and associated mold filling time. Although the VK440 gating system has the largest volume and heat capacity of the melt, it has also a larger casting surface and the melt in the mold until its completely filled remains longer. The longer filling time of the mold cavity allows the greater influence of the melt undercooling due to the contact with the mold face. At the same time, the larger surface of the runners generates larger heat exchange surface and thus allows more intense heat transfer and melt discharge into the mold.

In the runner No. 5 VK360 an optimal ratio was reached between the temperature capacityin the melt volume and the melt flow velocity.

Conversely, the melt in runner No.7 VK320, although having the highest velocity and remaining in the runner the shortest time, does not reach the highest temperatures. This could be due to the low melt volume in the runners, and thus to the sub-cooling due to lower heat capacity in the melt volume.

It is also worth noting that the temperature drops between measuring points 3.A/3.B and 4.A/4.B. This phenomenon is not only due to the fact that the measuring points 4.A/4.B have the largest average length of the melt flow l_{S4} and are therefore at the most distant point of the runner. The above mentioned temperature drop is caused by the measuring point. Measuring points 1.A/1.B to 3.A/3.B are located inthe zone that is heat affected by the heat transfer from the main runner to the mold, wherein 4.A/4.B is in zone that is not affected, and hence, is more subcooled by the influence of the temperature of the mold. Thus, it is possible to formulate a statement that when the ingate is located in a zone of the of heat affected mold by the main runner, the temperature drop due to the length of the runner is not remarkable.

7 Conclusion

Presented contribution deals with the optimization of the numerical design of the gating system using simulation program. The optimization was focused on the dimensions of the runners in order to achieve filling of the mold cavity by the melt reaching the highest possible temperature, keeping the constant input parameters settings.

After the simulation and evaluation of the considerated parameters, The VK360 gating system was the optimal solution for the runners. As has been shown, this solution provides the best ration between the temperature capacity in the melt volume and the melt flow velocity. On the basis of the optimization, shortening of the mold filling time was also achieved. For comparison, the time of one casting cycle from the start of the casting to the complete solidification of the cast was by the reference gating system No. 1 VK440 t_{c440} = 18,478s and by gating system No. 5 t_{c360} = 16,983s. Another noteable fact is the reduction of the volume of the gating system. If the volume of the runners by gating system VK440 was 351027.165 ^ 10^{-9} m^3, by optimization of the gating system VK360 was achieved volume of the runners 288331,609 ^ 10^{-9} m^3. The ultimate impact of the optimization is therefore also increase in production efficiency by shortening the casting cycles t_c and economical saving in the volume of waste produced or the return material reduction of the gating system volume.

It is clear that CAD/CAM support in the foundry area has an irreplaceable and important place. Although some of the smaller foundries are still hampered by the implementation of simulations in the technical preparation of production and rely on the experience of the main technologists. It is the implementation of simulation programs that, despite the higher purchase price, can lead to a significant increase in production efficiency and increased competitivness in the market, with the associated economic profit.

Acknowledgement

This paper has been prepared within the project VEGA 1/0041/16.

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10.21062/ujep/282.2019/a/1213-2489/MT/19/2/273
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