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MODEL TESTING OF CASTING PROCESS IN COLD-CHAMBER DIE CASTING MACHINE

BADANIA MODELOWE PROCESU ODLEWANIA W ZIMNNOKOMOROWEJ MASZYNIE CIŚNIENIOWEJ

Investigations of filling the model mould cavity (with perpendicular walls) of the casting die by model liquids of various density and viscosity are presented in the paper. Influence of localisation of the inlet system and inlet velocity on the flow character of model liquids of different viscosity in the system of a cold-chamber casting die was tested. Two Newtonian liquids were used as model liquids. They were obtained by adding the proper amount of water to glycerine, one liquid had a viscosity equal 1.39 cSt, corresponding to the viscosity of the liquid aluminium alloy, while the other 9.46 cSt. Observations of the filling process and the piston movement in the chamber recorded by filming constituted the bases for the estimation of the influence of the inlet velocity on the process of casting die filling – with taking into account the pressure, both in the pressing chamber and in the mould. A comparison of the experimental results with the calculated from the Reynolds Number for various viscosities and dimensions of inlet gaps was performed.
Keywords: diecasting, turbulent flow, laminar flow, model testing

W artykule przedstawiono badania zapełniania prostopadłościennej wnęki modelowej formy ciśnieniowej cieczami modelowymi o różnej gęstości i lepkości.

Badano wpływ usytuowania układu wlewowego oraz prędkości wlewowej na charakter przepływu cieczy modelowej o różnej lepkości w układzie zimnokomorowej maszyny ciśnieniowej. Jako ciecze modelowe w badaniach użyte zostały dwie ciecze newtonowskie, uzyskane przez odpowiedni dodatek wody do gliceryny, z których jedna miała lepkość 1,39 cSt, odpowiadającą lepkości płynnego stopu aluminium, natomiast druga lepkość 9,46 cSt. Obserwacje zapełniania oraz ruchu tłoka w komorze prasowania utrwalone za pomocą filmowania stanowiły podstawę do oceny wpływu granicznej prędkości wlewowej na proces zapełniania formy z uwzględnieniem ciśnienia w komorze prasowania i w formie. Przeprowadzono również porównanie wyników eksperymentalnych z rezultatami obliczonymi z liczby Reynoldsa dla różnych lepkości i wymiarów szczelin wlewowych.

1. State of art in model testing of die casting process

1.1. Modelling investigations of the 1st phase of the pressure die casting

The theory of the liquid metal flow in a squeeze chamber, described in terms of a general theory of the fluid flow, has been mainly based on the results of simulation made on the continuously improved mathematical models [1]. The first pioneer theoretical model applying the law of flow continuity and Bernoulli's law of the stationary flow of incompressible liquids, enabling determination of height T and velocity v_w, of movement of the wave formed on the stream head and caused by a predetermined speed of the squeeze plunger travel v_p (Fig. 1), was developed by Garber [2] at the beginning of eighties of the past century. The model suggested that in an ideal liquid the height of the wave and its velocity depend on the diameter of the squeeze chamber and on the ratio of its initial filling with molten metal. Garber established, moreover, the value of a "critical speed" for plunger of a given diameter, which is said to be responsible for the formation of a wave filling the squeeze chamber and is helpful in reducing to minimum the disadvantageous effect of air occlusion.

The model developed by Garber described the final shape of a headwave formed after the moment when the plunger stops receiving any acceleration and its movement can assume a constant speed. Garber's model offered some possibilities of determining the parameters of

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a single wave (its height mainly) moving along the liquid resting in a squeeze chamber, where the height of this liquid is corresponding to an initial ratio of the chamber filling with molten metal. This problem has been allowed for in the, so called, modified Garber's model proposed by Thom and Brevick [3]. Another model, relating the wave height to the speed of the squeeze plunger, to an initial value of the chamber filling ratio and chamber diameter, was developed by Karni in [4]. On the other hand, Madsen and Svendsen [5] created a model applying the theory of hydraulic shock and turbulent flow, and assuming a square cross-section of the squeeze chamber. To allow for an influence of the initial plunger acceleration, Tszeng and Chu [6] developed a model used for computation of the resultant height and speed of the waves, corresponding in the squeeze chamber to an increase of the squeeze plunger speed, repeated every single time.

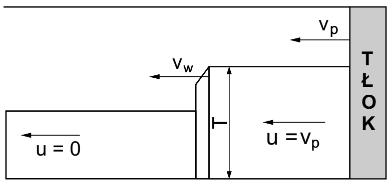


Fig. 1. Schematic representation of a wave head formed by plunger moving in the squeeze chamber of a cold-chamber diecasting machine [2]

An essential supplement into existing models of the I phase of die casting process was introduced by J. Stojek [7] and others, who have provided possibility of determining what effect the changing viscosity of liquid metal may have on the flow phenomena at the process stage examined here, and specially on the severity level of the forming air occlusion.

To better examine the flow phenomena which occur during Phase I of the die casting process, and to examine what effect the changes in liquid metal viscosity may have on the occurrence of air occlusions, at the Faculty of Process Automation, in cooperation with the Department of Foundry Machines and Equipment, University of Sciences and Technology in Cracow, a pilot post has been designed and constructed, and a physical model of the squeeze chamber operating in a cold-chamber die casting machine was provided. The stand for model studies of Phase I of the die casting process have been presented in papers [9, 11, 12].

The value of occlusion OF was expressed as a field of the liquid stream cross-section area affected by occlusion. The studies were conducted with a step-wise change in the signal controlling the squeeze plunger travel speed. Knowing that a good approximation of the results of the measurements will be obtained, it has been decided to use a polynomial of the second order:

$$OF = c_0 + c_1 \cdot v + c_2 \cdot \upsilon + c_{11} \cdot v^2 + c_{22} \cdot \upsilon^2 + c_{12} \cdot v \cdot \upsilon \quad (1)$$

for which the coefficients c_0, c_1, c_2,...,c_{12} had to be calculated.

The experiments were performed for four ratios of the squeeze chamber filling with model liquids (ϕ = 50%, 60%, 70%, 80%). An example of the forming wave with distinctly visible zone of the liquid with air occlusion is shown in Figure 2.

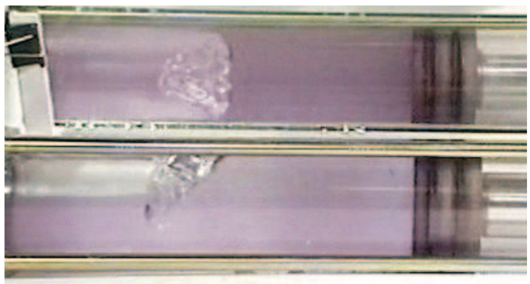


Fig. 2. Top and side view of the liquid stream area affected by air occlusion

The results of the studies processed to give the air occlusion characteristics OF in function of the squeeze plunger travel speed v and kinematic viscosity υ of model liquid for four ratios of the squeeze chamber filling are given in Table 1.

TABLE 1

Polynomials describing an effect of kinematic viscosity and plunger speed on the value of occlusion related to the squeeze chamber filling ratio ϕ [7]

ϕ	Derived function
50%	$OF = 31.024 - 137.398 \cdot v - 0.425 \cdot \upsilon + 166.219 \cdot v^2 + 0.001 \cdot \upsilon^2 + 0.865 \cdot v \cdot \upsilon$
60%	$OF = 18.0868 - 94.1801 \cdot v - 0.2154 \cdot \upsilon + 127.491 \cdot v^2 - 0.000026 \cdot \upsilon^2 + 0.621 \cdot v \cdot \upsilon$
70%	$OF = -1.984 + 12.0437 \cdot v$
80%	$OF = -1.37266 + 7.03323 \cdot v$

where: OF – the value of air occlusion on wave head [cm^2], v – the squeeze plunger travel speed [m/s], υ – the coefficient of kinematic viscosity of model liquid [mm^2/s].

Basing on the results of the studies, an effect of changes in kinematic viscosity υ of model liquid on the recommended critical plunger speed v_{kryt}, i.e. the speed which the squeeze plunger should adopt to reduce as much as possible the area of the liquid stream affected by air occlusion, was determined. This enabled introducing some modifications to Garber's equation described in [3] and its further extension by a correlating factor Δv, allowing for the kinematic viscosity of cast alloy (equation (2)). The studies described in this paper have proved that Garber's equation requires application of a correlating factor at the starting stage of filling the squeeze chamber with molten metal up to a ratio of $\phi < 70\%$. Above this ratio, the obtained results indicate no immediate effect of model liquid viscosity υ on the value of the formed occlusion OF.

So, at the starting ratio of the squeeze chamber filling with molten metal equal to $\phi = 50\%$, the true speed of the squeeze plunger movement will be:

$$v_{rzecz50\%} = v_{kryt} - \Delta v_{50\%}, \tag{2}$$

where: $v_{rzecz50\%}$ – the true value of the squeeze plunger movement speed for a starting ratio of the squeeze chamber filling with molten metal equal to $\phi = 50\%$ [m/s], v_{kryt} – the squeeze plunger movement speed determined from Garber's equation (the, so called, critical speed) for a starting ratio of the squeeze chamber filling with molten metal equal to $\phi = 50\%$ [m/s]

$$v_{kryt} = \sqrt{\frac{2 \cdot g \cdot (J - D) \cdot (\beta - \phi)}{(\beta + \phi)}},$$

where: J – the height of molten metal column behind the headwave [m], D – the height of molten metal column in front of the headwave [m], β – the share of the squeeze chamber cross-section area filled with molten alloy behind the wave head (the chamber filling ratio behind the wave head) [–], ϕ – the share of the squeeze chamber cross-section area filled with molten alloy directly in front of the wave head (the starting value of the chamber filling ratio) [–], υ – the kinematic viscosity of molten alloy at a pouring temperature [mm^2/s], $\Delta v_{50\%}$ – the correction factor for squeeze plunger speed at the chamber filling ratio equal to $\phi = 50\%$

$$\Delta v_{50\%} = 0.07385 + 0.00272 \cdot \upsilon.$$

Finally, for the chamber filling ratio of $\phi = 50\%$ the following equation was derived:

$$v_{rzecz50\%} = \sqrt{\frac{2 \cdot g \cdot (J - D) \cdot (\beta - \phi)}{(\beta + \phi)}} - (0.07385 + 0.00272 \cdot \upsilon). \tag{3}$$

Consequently, for the starting ratio of the squeeze chamber filling equal to $\phi = 60\%$ the true speed of the squeeze plunger will be:

$$v_{rzecz60\%} = v_{kryt} - \Delta v_{60\%}, \tag{4}$$

where:

$$\Delta v_{60\%} = 0.07384 + 0.000258 \cdot \upsilon.$$

In its final version, the modified Garber's equation for the starting ratio of the squeeze chamber filling equal to $\phi = 60\%$ assumes the following form:

$$v_{rzecz60\%} = \sqrt{\frac{2 \cdot g \cdot (J - D) \cdot (\beta - \phi)}{(\beta + \phi)}} - (0.07384 + 0.000258 \cdot \upsilon). \tag{5}$$

1.2. Model investigations of the 2nd phase of the pressure die casting

In the case, when parameters of the pressure die casting process do not ensure stable and planned running of the process the obtained casting can have defects lowering its mechanical properties. Therefore, the guarantee of the proper filling of the mould cavity by liquid metal in the conventional die casting process and elimination of unfavourable phenomena, such as air pockets (gaseous porosity of castings) and oxide inclusions is very important. Maintaining the inlet velocity at 0.3–0.5 m/s in the conventional technology of pressure die casting, leads to stable and planned filling of the casting die – found the authors of the paper [11]. However, due to a relatively low inlet velocity this process is not suitable for production of thin-walled castings, because during a fast casting solidification there is a possibility of formation of shrinkage cavities.

When the process of metal pressing is done at its thixoforming state, in which input material constitutes a mixture of phases of high viscosity, it is possible to control a laminar flow of liquids. In this case the limiting inlet velocity, which depends also on the runner system geometry can be equal up to 2.5 m/s [11]. If the produced castings are to be applied in airtight structures the elimination of formation of air pores and oxide layers in castings by controlling the alloy flow in its thixoforming state is extremely important. Therefore certain parameters of the process, such as: geometry of the runner system, inlet velocity and mould temperature must be controlled in order to ensure stable and planned filling.

Due to difficulties related to safety of the visualization the filling process of the casting mould with liquid metal in the real time, the influence of the selected parameters is being determined – up to the present – on the basis of the so-called filling tests [2÷6].

In those tests the movement of the pressing piston, controlled by an electronic system operating in the real time, is stopped in the assumed position. The method is successfully applied in the case of a low inlet velocity and simple geometrical structure of the mould. However, in the case when the inlet velocity increases the method does not allow maintaining the flow character at the assumed moment. Therefore the majority of investigations of the influence of process parameters on the flow character have been performed on the grounds of a computer software based on hydrodynamic calculations [7÷9].

Methods of visualisation of filling mould cavities with metal can constitute a useful tool for the estimation of the influence of individual parameters on the flowing process as well as for the verification of the obtained experimental results with the computer simulation results.

Therefore the aim of our own research [12] and others [11] is the estimation of the influence of the runner system geometry and inlet velocity of aluminium alloy in a thixoforming state or model liquids of the determined viscosity characteristics on phenomena occurring during filling the mould. The development of the visualization method of the process was an additional purpose of our investigations. The comparison of the experimental results with the ones calculated from the Reynolds Number is presented in the paper.

2. Stand for model investigations of the 2nd phase of the pressure die casting

Essential elements of the stand for model investigations of the 2nd phase of the pressure die casting are illustrated in Fig. 3. The detailed description of the stand is given in papers [10, 12]. Its main element is the horizontally situated model of the pressing chamber, made in 1:1 scale, together with the pressing piston and the model of casting mould. In order to make visualization of the flow possible, the chamber as well as the mould were made of colourless and transparent plastics. The pressing chamber model is made from a colourless extruded pipe of PMMA of an internal diameter ϕ 70 mm and the chamber length of 500 mm. The mould of a rectangular cross-section and dimensions 280 mm (height) × 190 mm (width) and of an adjustable thickness, which can be equal 25, 15, 10 and 5 mm (by application of inserts) – was used in experiments. Two inlet systems of a rectangular cross-section were applied. Both systems, which could be placed in the middle of the bottom wall of the mould or from its left or right side, had the same width of 48 mm but different thickness of 3 and 4.7 mm.

Construction of the stand enables an easy installation of the needed sensors and measuring converters, for which the proper sockets and holders were mounted. Modern pressure converters type MBS-32 of the Danfoss Company, were used for measuring pressure in the pressing chamber and in the mould. Magnetostrictive linear converter, type BTL2 of the Balluf Company, was used for measuring the pressing piston shifting. It is a contact-less converter of high accuracy of measurements, suitable for operation in heavy industrial conditions (among others in casting machines). The measurement of a piston acceleration is realized by means of the acceleration converter, made from integrated elements type ADXL50 of the Analogue Devices Company. Phenomena occurring in the model pressing chamber – during the piston movement – are recorded, at the proper lighting, by the video camera and then processed by computer.

Fig. 3. View of the stand for analysis of the flow phenomena occurring during filling the mould of the pressure die casting with the model liquid

Model liquids

Two Newtonian liquids of different viscosities and densities were used as model liquids. They were obtained by the proper dilution of glycerine with added distilled water. The experiment were performed for the model liquid of a kinematic viscosity equal 1.39 mm^2/s (1.39 cSt), marked “CIECZ 7%”, which in approximation corresponds to the viscosity of the liquid aluminium alloy at the pressure die casting. The second liquid of the viscosity 9.46 mm^2/s (9.46 cSt) – marked “CIECZ 80%”, can represent viscosity of other aluminium alloys at casting at the tixoforming state.

Visualisation of flowing

Time needed for a complete filling of the casting die depends on its thickness and on the velocity of filling. This time is in the range 0.03÷0.5 s. [11] in the real technological process. In model experiments those times were longer, practically by one order of magnitude, because we limited to 5 m/s the velocity of shifting the pressing piston. To preserve flow phenomena occurring during filling the casting die the method of fast photography or filming with the speed of 25 pictures in a second, were applied.

On the grounds of observations a qualitative estimation of the character of flow – by introducing two different types of flow – was applied. Notation "laminar flow" or "layered flow" was used in the case, when liquid was filling the mould in a stable way, it means when neither air bubbles occlusion nor unstable meniscus was formed. Notation "turbulent flow" or "non-layered flow" was used in the case, when the meniscus was unstable or broken and blowholes, in which model liquid could be locked, formed.

The recording speed depended on the liquid flow velocity in the runner gap. On the basis of the filmed process the verification of a flow intensity of the model liquid injected into the mould was performed. The model liquid velocity in the inlet was determined by multiplication the cross-section surface of a piston by the coefficient expressing the ratio of the lateral cross-section surface of the pressing chamber to the lateral cross-section surface of the inlet system. The applied values of piston shifting were: 0.07 m/s and from 0.1 to 0.5 m/s with an interval of 0.05 m/s. Velocities of the model liquids in the runner – corresponding to these values – are listed in Tables 2÷4.

3. Results

The list of data given in Tables 2, 3 and 4 concerns parameters and type of filling the mould by model liquid via runners 3 × 48 mm and 4.7 × 48 mm. Different ways and values of venting surfaces located at the mould top were applied. Venting system marked as O-O-O means that three venting channels were open. One channel was placed in the longitudinal axle of the mould, while the remaining two were located symmetrically versus the axle at a distance of approximately 90 mm each. Active surface of ventings is $3 \times 17.34\ mm^2 = 52\ mm^2$. Venting system marked O-Z-O means, that the central channel is plugged, while the side channels surface is reduced to $2 \times 8.04\ mm^2 = 16.08\ mm^2$. Venting with symbol Z-O-Z represents the situation, in which both side channels are plugged and the central channel open (of active venting surface equal $8.04\ mm^2$).

Analysis o f a model liquid flow rate

Analysis of a model liquid flow rate given in Tables 2÷4 indicates that there are significant differences in between the velocities in the runner gap. The highest value of the model liquid flow rate, calculated on the grounds of the pressure measurement in the shot sleeve and in the mould cavity, occur in the velocity interval 2.67÷4.0 m/s for the runner gap 3 × 48 mm and in the range 2.56÷3.41 for the runner gap 4.7 × 48 mm. In the first case it corresponds to the velocity of the pressing piston being in the range: 0.1÷0.15 m/s, while in the second case to the one in the range: 0.15÷0.20 m/s. In both cases the Re Number is close to the value 2100 indicating the laminar type of the model liquid flow, however visual observations of the filling process reveal partially not stable flows. It can be noticed, that for both runners the flow rate of model liquid determined on the basis of filming the filling process, are significantly lower from values obtained by the described previously method. Regardless of that, the local maximum of discharges occurs at such velocity for which discharges calculated previously have the lowest values. Reasons of this apparent paradox can be explained by the fact that lower discharges are caused by two factors. One of the factors is an "escape" – via venting channels – of certain amount of liquid, which during the filling process is transported together with air leaving the cavity through these channels. The second factor influencing lowering the liquid discharge expressed in cm3/s, is a longer total time of the process comprising the time of filling the cavity with highly dispersed mixture of liquid and air as well as the time needed for the evacuation of 'being occluded" small air bubbles into venting channels and for killing the liquid circulation. The mentioned above phenomena occur at certain pressure in the mould, often after surpassing the maximum value in the shot sleeve, and this cannot be quantitatively determined from the graph of pressure versus time. Thus the conclusion, that more reliable estimation of flow phenomena is based on visualizations, seems to be justified. The pressure recording should be considered only as an auxiliary tool, useful at stability estimations of the investigated processes.

Phenomena occurring during filling the mould with the higher viscosity liquid

As an example, 2 series of photographs taken during the process of filling the mould with the tested model liquids – introduced from the bottom runner into the mould of 10 mm thickness at the inlet velocity range: 1.7÷8.52 m/s, are presented in Fig. 4 and 5. The runner system of dimensions 4.7 × 48 mm, centrally located (Fig. 4) and shifted to the right hand side of the mould cavity (Fig. 5) was applied. When the inlet velocity of an liquid filling the mould is slower than approximately 2.5 m/s, a convex meniscus is formed on its surface leading to the laminar flow. When, the inlet velocity increases the flow becomes more and more unstable and at velocities higher than 4 m/s the free surface of the liquid breaks, what captures blowholes inside the model liquid. At the velocities above 10 m/s a stream of liquid becomes broken and the liquid surrounds several small blowholes of fuzzed shapes.

TABLE 2

List of data concerning parameters and kind of mould filling with the model liquid “CIECZ 80%”, via inlet gaps 3 x 48 and 4.7 x 48 m. Venting system: O-O-O.
Active venting area 3 x 17.34 mm^2 = 52 mm^2

No	Piston velocity [m/s]	Velocity [m/s] and Re Number in the inlet gap of dimensions: a x b [mm]		Flow rate of model liquid [cm^3/s]: R-Real, T – Theoretical, E – Ratio: R/T		Pressure [bar]: A. Press. chamber, B. Mould cavity, C. Ratio: B/A		Flow rate of model liquid determined by photo analysis [cm^3/s]:	Character of mould filling (photo analysis)
		3 x 48	4.7 x 48	3 x 48	4.7 x 48	3 x 48	4.7 x 48	4.7 x 48	
1.	0.07	1.87 Re 1116	1.19 Re 1077	R. 175.0 T. 269.4 E. 0.649	R. 137.4 T. 269.4 E. 0.51	A. 0.67 B. 0.40 C. 0.54	A. - b.d. B. 0.55 C. - b.d	137.1	stable
2.	0.10	2.67 Re 1593	1.70 Re 1540	R. - b. d. T. - b.d. E. - b.d.	R. 203.50 T. 384.8 E. 0.53	A. - b.d. B. - b.d C. - b.d.	A. - b.d. B. 0.65 C. - b.d.	187.3	stable
3.	0.15	4.00 Re 2387	2.56 Re 2316	R. 324.2 T. 612.9 E. 0.650	R. 274.3 T. 612.9 E. 0.45	A. 1.10 B. 0.56 C. 0.51	A. - b.d. B. 0.80 C. - b.d.	260.8	partially stable
4.	0.20	5.34 Re 3187	3.41 Re 3100	R. 357.5 T. 771.0 E. 0.090	R. 363.0 T. 777.1 E. 0.470	A. 1.40 B. 0.65 C. 0.46	A. - b.d. B. 0.92 C. - b.d.	277.1	unstable
5.	0.25	6.68 Re 3987	4.26 Re 3856	R. 295.5 T. 962.0 E. 0.307	R. 324.4 T. 962.0 E. 0.34	A. 1.60 B. 0.65 C. 0.41	A. - b.d. B. 1.12 C. - b.d.	316.6	unstable
6.	0.40	10.68 Re 6375	6.82 Re 6172	R. 380.0 T. 1539 E. 0.247	R. 433.6 T. 1539 E. 0.28	A. 2.50 B. 0.95 C. 0.38	A. - b.d. B. 1.03 C. - b.d.	289.1	turbulent
7.	0.50	13.36 Re 7975	8.52 Re 7700	R. 391.5 T. 1924 E. 0.203	R. 494.8 T. 1924 E. 0.26	A. 3.00 B. 1.50 C. 0.50	A. - b.d. B. 1.20 C. - b.d.	271.4	turbulent

TABLE 3

List of data concerning the influence of mould venting system on the flow rate of model liquid, determined on the basis of pressure measurements and filming the filling process. Runner 3 × 48 mm

No	Pressing piston velocity [m/s]	Velocity [m/s] in the runner 3 x 48 mm	Flow rate of model liquid determined on the basis of pressure in the shot sleeve and in the mould cavity [cm^3/s]			Flow rate of model liquid determined by photo analysis [cm^3/s]:	
			Type and venting area [mm^2]				
			O-O-O 52.00	O-Z-O 16.08	Z-O-Z 8.04	O-Z-O 16.08	Z-O-Z 8.04
1.	0.07	1.87	175.0	153.3	-	131.68	127.4
2.	0.10	2.67	-	-	244.7	175.00	171.0
3.	0.15	4.00	324.2	324.9	371.0	241.10	209.6
4.	0.20	5.34	357.5	335.2	353.9	217.0	182.19
5.	0.25	6.68	295.5	214.2 T.	223.8	170.50	197.0
6.	0.40	10.68	380.0	304.3	280.6	204.6	195.6
7.	0.50	13.36	391.5	371.4	302.6	258.80	183.2

TABLE 4

List of data concerning the influence of mould venting system on the rate of model liquid flow, determined on the basis of pressure measurements and filming the filling process. Runner 4.7 × 48 mm

No	Pressing piston velocity [m/s]	Velocity [m/s] in the runner 3 x 48 mm	Flow rate of model liquid determined on the basis of pressure in the shot sleeve and in the mould cavity [cm^3/s]			Flow rate of model liquid determined by photo analysis [cm^3/s]:		
			Type and venting area [mm^2]					
			O-O-O 52.00	O-Z-O 16.08	Z-O-Z 8.04	O-O-O 52.00	O-Z-O 16.08	Z-O-Z 8.04
1.	0.07	1.19	222.6	172.7	186.2	137.1	133.0	127.9
2.	0.10	1.70	246.0	-	281.0	187.3	183.4	168.3
3.	0.15	2.56	333.5	368.0	414.1	260.8	266.0	225.4
4.	0.20	3.41	363.0	385.0	493.5	277.1	282.9	271.4
5.	0.25	4.26	386.7	293.0	311.7	316.6	289.1	237.5
6.	0.40	6.82	481.7	438.3	500.5	289.1	250.9	229.3
7.	0.50	8.52	553.3	418.2	400.6	271.4	229.3	201.5

Analysis of successive pictures shows that at higher velocities in inlet gap shows that a stream of liquid faster enters into a dispersed state.

Phenomena occurring during the mould filling with the lower viscosity liquid were observed for the model liquid “CIECZ 7%”. Tests contained also the mould filling by the inlet system of a width 3 and 4.7 mm, at various velocities.

At velocities above 1.7 m/s the process for both width of inlet gap is not stable. The liquid metal meniscus becomes unstable and a turbulent flow forms. Comparison of these results with the ones obtained for the model liquid “CIECZ 80%” allows to notice that achieving the required metal flow is much easier for liquids of the higher viscosity. It has a practical relation to the selection of the pressure die casting technology, indicating that the mould filling by metal in tixoforming state is more stable – even at higher velocities – than by fully liquid metal. Character of a liquid flow in a pipe of a circular cross-section can be determined by the dimensionless coefficient, called Reynolds Number, which value for the laminar flow ($Re \leqslant 2100$) can be used for calculating the critical velocity of a liquid stream in the inlet gap. $Re > 2100$ indicates the turbulent flow.

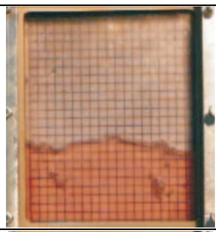
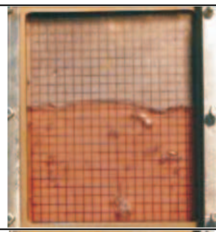
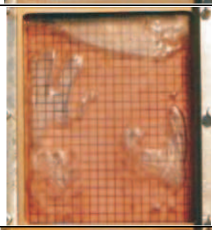
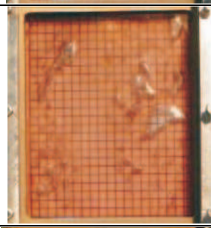
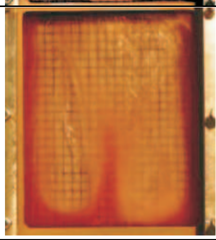
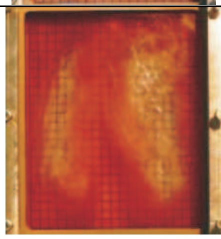
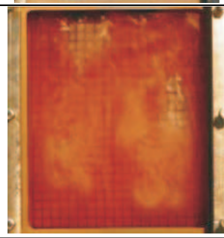
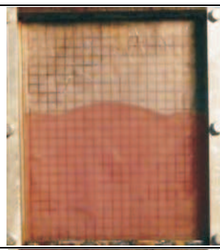
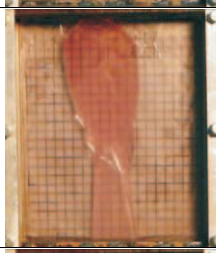
The central runner		**DATA:** Mould cavity**:** 280 x 190 x 10 mm, V_f = 0.532 dm^3, runner size 4.7 x 48 mm, Runner surface f_{wlew} = 225.6 mm^2. Type and active venting surface**:** O -O-O, F_{odp} = 52.00 mm^2. **Model liquid**: "CIECZ 7%", viscosity υ_l = 1.39 mm^2/s; density ρ_l = 1.05 g/cm^3		
		Time of filling 0.32 s	Time of filling 1.0 s	Time of filling 1.56 s
Pressing piston velocity. (Velocity v_w in the runner), [m/s]	0.1 (1.70) **Re 1047**			
	0.2 (3.41) **Re 21004**			
	0.5 (8.52) **Re 52480**			
		DATA: Mould cavity and nventing system the same as presented above. **Model liquid**: "CIECZ 80%", viscosity υ_l = 9.46 mm^2/s; density ρ_l = 1.12 g/cm^3		
		Time of filling 0.32 s	Time of filling 1.0 s	Time of filling 1.56 s
	0.1 (1.70) Re **1540**			
	0.2 (3.41) **Re 3100**			
	0.5 (8.52) **Re 7700**			

Fig. 4. Selected phases of filling the mould with model liquids at various parameters of the process. Inlet runner placed centrally

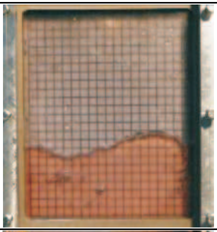
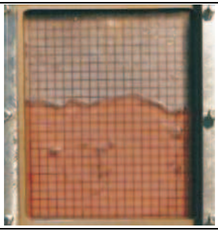
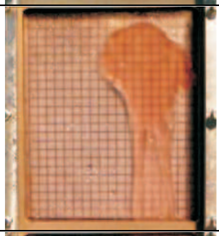
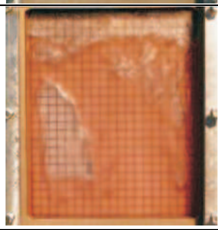
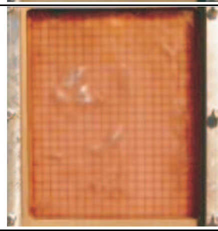
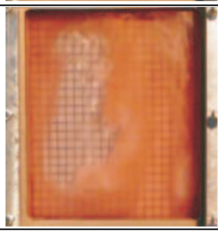
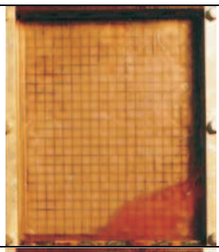
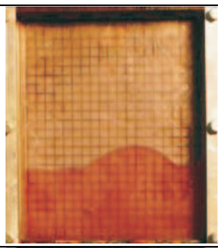
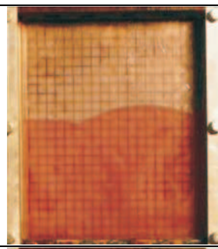
Right side runner		**DATA:** Mould cavity: 280 x 190 x 10 mm, V_f = 0.532 dm^3, runner size 4.7 x 48 mm, Runner surface f_{wlew} = 225.6 mm^2. **Type and active venting surface:** O -O-O, F_{odp} = 52.00 mm^2. **Model liquid**: "CIECZ 7%", viscosity υ_l = 1.39 mm^2/s; density ρ_l = 1.05 g/cm^3		
		Time of filling 0.32 s	Time of filling 0.32 s	Time of filling 0.32 s
Pressing piston velocity. (Velocity v_w in the runner), [m/s]	0.1 (1.70) **Re 1047**			
	0.2 (3.41) **Re 21004**			
	0.5 (8.52) **Re 52480**			
		DATA: Mould cavity and nventing system the same as presented above. **Model liquid**: "CIECZ 80%", viscosity υ_l = 9.46 mm^2/s; density ρ_l = 1.12 g/cm^3		
		Time of filling 0.32 s	Time of filling 0.32 s	Time of filling 0.32 s
	0.1 (1.70) Re **1540**			
	0.2 (3.41) **Re 3100**			
	0.5 (8.52) **Re 7700**			

Fig. 5. Selected phases of filling the mould with model liquids at various parameters of the process. Inlet runner placed at the right hand side of the mould

A viscosity range from 1.39×10^{-6} m^2/s to 9.46×10^{-6} m^2/s for the investigated model liquids means simultaneously the same value of the expression:

$$v_w \cdot D_e \leqslant (1.39 \div 9.46) \times 10^{-6}\ [m^2/s], \qquad (6)$$

where: v_w – limiting inlet velocity, below which the laminar flow occurs.

For runner of a rectangular cross-section factor D_e in equation (6) can be substituted by an equivalent expression:

$$D_e = \frac{2wt}{(w+t)}, \qquad (7)$$

where: w and t – width and thickness of the inlet runner – respectively.

The calculated velocity for the liquid "CIECZ 7%" equals 0.3÷0.5 m/s and for "Ciecz 80%" equals 2.3÷3.5 m/s for Re = 2100 and an equivalent diameter D_e = 0.005647 m (runner: 3 × 48 mm) and D_e = 0.008362 m (runner 4.7 × 48 mm).

Relating the obtained results of model testing e.g. to liquid Al alloy of a viscosity equal $2.23 \times 10^{-6} m^2/s$ at a temperature 595°C the recommended velocity range 0.55÷0.83 m/s is obtained for the tested dimensions of the inlet gap.

For Al. alloys in the tixoforming state, for which a dynamic viscosity equals 1÷2 Pa·s ($4 \div 8 \times 10^{-5} m^2/s$) and density 2500 kg/m^3 the analogical expression (to (7)) is of the form:

$$v_w D_e \leqslant 0.084 \sim 0.168\ \ (m^2/s) \qquad (8)$$

and the range of the calculated velocity in the inlet gap equals 15÷20 m/s.

The above considerations indicate, that such parameters as the inlet system geometry and inlet velocity influence the type of the model liquid flow, which is related to the quality of the obtained die castings.

4. Conclusions

The following conclusions can be formulated on the basis of the flow phenomena photographs taken in the real time as well as on the basis of measuring the flow ratio of model liquids:

1. Both the geometry of the mould inlet system and the inlet velocity influence the flow character during the mould filling. At the constant inlet velocity the type of flow depends more on the thickness of the inlet system than on its width. Thus, the critical inlet velocity is inversely proportional to the thickness of the runner.
2. The experimental results confirm the ones calculated on the grounds of the Reynolds Number. At the current situation of pressure die casting, where inlet systems of a thickness up to 10 mm, the inlet velocity of the range 0.3÷0.5 m/s is considered the proper one for obtaining the flow of the planned character. In the case of the pressing process in the tixoforming state the inlet velocity can be of a higher value (by one order of magnitude) without changing the type of flowing.
3. Stable flow processes of model liquid or metal are much easier obtained when a liquid of higher viscosity is used.

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