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The Piston Velocity Impact on the Filling Chamber Wave Formation of High Pressure Die Casting Machine in 1st Phase of Casting Cycle

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The quality properties of high pressure die casts are closely correlated with porosity. The formation of porosity is primarily initiated by entrapment of air and gases in the volume of the melt, during its transition through the gating system. This entrapment can occur as a result of an incorrect design of the gating system, incorrect setting of the casting technological parameters, or sometimes a combination of both causes. The setting of the piston velocity in the first and second phase of the casting cycle has the highest proportion of the gas entrapment of all the technological parameters. The submitted article is describing the influence of piston velocity in the first phase of the casting cycle. Velocities are investigated in range from 0.1 m.s^{-1} to 1.3 m.s^{-1}. First of all, the development of the wave arising at different piston velocities is assessed and the gas entrapment in the melt volume is investigated. Subsequently, the proportion of the gas entrapment in the cast volume at the end of the filling phase is investigated depending on the variable value of the piston velocity in the first phase. In the end, the determination of the piston velocity impact in the first phase on the completion nature of the filling chamber of the machine is derived.

Keywords: HPDC, Piston velocity, Gas Entrapment, Porosity, Chamber Filling

1 Introduction

The High pressure die casting method (HPDC) is typically used to mass production of aluminium alloy casts. High pressure die casts are characterized by high geometric accuracy, good mechanical properties and low price [1][2]. Mechanical properties of the casts are closely related to the formation of a fine-grained structure during rapid cooling of the melt in contact with the face of the mold, however, defects such as porosity, primarily caused by gas entrapment by the melt in the filling phase, significantly affect the quality of the casts [3][4].

Gas entrapment by the melt and associated reduction of the casts porosity can be eliminated by appropriate treatment of the melt, by setting the technological parameters of the casting cycle and, last but not least, by the correct design of the gating system [5][6]. Among the most important factors in the high pressure die casting is the piston velocity in the filling chamber of the machine. This velocity determines the way the mold cavity is filled and thus affects the internal and surface quality of the casts. The piston velocity is the determining factor on which the melt velocity in the gating system and in the gate depend. The melt velocity in the gate determines the mode of filling the shaped cavity of the mold, which directly affects the internal health of the cast, with which the mechanical properties of the casts are closely correlated. Choosing the correct mold cavity filling velocity depends on factors such as the type of alloy, the complexity of the cast, the thickness of the cast walls and the ratio between the gate cross-section and the cross-section of the cast [7][8].

The movement of the pressing piston in the filling chamber, and its associated velocity, can be divided into two phases. In the first phase, the so-called low pressure, the piston accelerates and the melt is pushed towards the biscuit under the influence of the piston. Most of the gases are pushed from the filling chamber in front of the melt flow face out of the filling chamber and subsequently out of the mold through the venting system. Part of the gases in the filling chamber can be trapped in the melt volume, while the gas entrapment volume is largely determined by the shape of the generated wave [9]. The reduced velocity in the first phase of the piston movement is beneficial for the continuous expulsion of gases from the filling chamber of the machine. In practice, the piston velocity in the first phase of its movement is selected in the range of 0.1 m.s^{-1} – 0.3 m.s^{-1} , but in no case should it exceed the values of 0.9 m.s^{-1} [10][11].

In the second phase of the piston movement, there is a rapid increase in the piston velocity up to the maximum value. The transition time from the first to the second phase of the piston movement is often selected in practice at the moment when the melt in the gating system reaches the gate. A certain amount of gases are trapped in the cast as a result of the filling mode of mold cavity. In real conditions, the filling mode of the mold cavity achieved is showing turbulent flows with dispersive character [9][12][13].

As mentioned above, the selection of optimal melt velocity, and therefore the mold cavity filling velocity, depends on many variable factors. For the casting of aluminum alloys, it is possible to set the optimal velocity of the melt in gate based on the diagram at Fig. 1 [11].

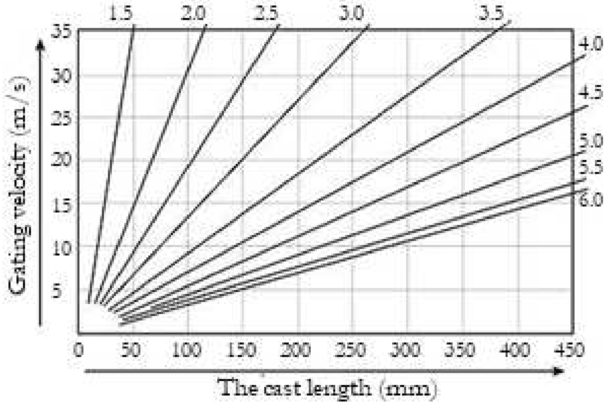

***Fig. 1** Dependence of optimal gating velocity on the characteristic dimensions of the cast [11]*

If the gating system is considered as a closed system, the piston velocity in the second phase can be determined based on the continuity equation, according to the relation [14]:

$$S_G . v_G = S_P \cdot v_{p2} \quad (1)$$

Where:
S_G ...Gate Area [mm],
S_P ...Piston Area [mm],
v_G ...Gate velocity [m.s^{-1}],
v_{p2} ...Piston velocity in 2nd phase [m.s^{-1}].

Determination of the piston velocity in the second phase - v_{p2}, is based on empirically determined relations derived on the basis of knowledge of thermomechanics and hydromechanics. To determine the piston velocity in the first phase - v_{p1} such expressions are not conceived, therefore it is necessary to derive the setting of this velocity on the basis of generally valid recommendations based on the practical experience of foundry technologists [15][16].

In general, the effort is to choose the highest possible degree of chamber filling. The principle applies that a low degree of filling promotes the swirling of the metal in the filling chamber, and therefore it is necessary to avoid this phenomenon. It is important to set the piston velocity in the first phase so that the formed wave of metal fills the entire cross-section of the filling chamber. In this way, a gas pocket is not created in the upper part of the filling chamber, which could be entrapped in the metal stream. Therefore, there is a critical piston velocity v_{crit} (Fig. 2), at which, at a given initial degree of chamber filling, together with the piston diameter such a wave is created that covers the entire front side of the piston. In this way, a wave of metal is created on the front side of the piston, which does not separate from it and moves at the same velocity as the piston, its height increases and it pushes the gases from the filling chamber in front of it through the mold venting system and in this way allows the metal to be inflated without unnecessary turbulence and without gas entrapment in the volume of metal [17][18][19].

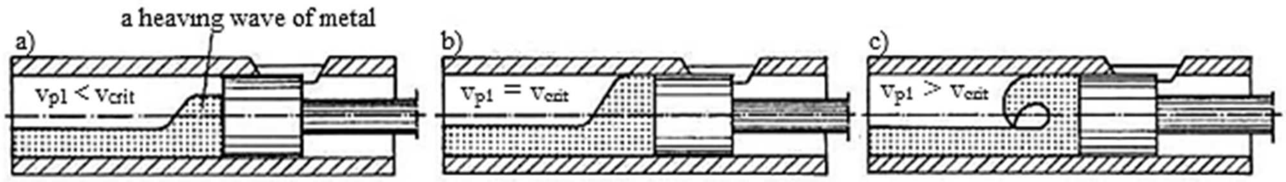

***Fig. 2** Wave formation depending on the ratio of the speed v_{p1}/v_{crit}*

Since the exact determination of the piston velocity in the first phase of the pressing cycle is not explicitly defined and is governed only by generally accepted recommendations, the submitted article solves the problem of the development and the formation of a wave of liquid metal in front of the face of the pressing piston depending on the variable piston velocity in the first phase v_{p1}. The experiments presented in this paper were performed with the aim of describing the influence of the piston velocity in the first phase on the formation of the liquid metal wave in the filling chamber, and to determine the method of gas entrapment in the liquid metal volume depending on the variable piston velocity in the first phase of the pressing cycle. The process of overfilling the casting chamber during the piston movement was monitored using the Magmasoft 5.4 program. The development and shaping of the heaving wave of metal was monitored at the piston velocity v_{p1} with a maximum value of 0.1 m.s^{-1}, 0.2 m.s^{-1}, 0.3 m.s^{-1}, 0.4 m.s^{-1}, 0.5 m.s^{-1}, 0.7 m.s^{-1}, 0.9 m.s^{-1}, 1.1 m.s^{-1} and 1.3 m.s^{-1}. Depending on these values, the percentage of gas entrapment in the volume of casts at the end of the filling phase was monitored. The gas entrapment in the cast volume was evaluated at the time just before the start of the holding pressure phase, when the mold cavity is filled to 100%. This period of time was selected with regard to the fact that the holding pressure significantly reduces the gas entrapment, affects the size and distribution of the pores, which directly reduces the porosity of the casts.

By simultaneously monitoring the formation of a wave of liquid metal in front of the face of the pressing piston depending on the variable piston velocity in the first phase and gas entrapment in the cast volume at the end of the filling, it was possible to determine the mutual correlation of these parameters. Based on the conducted experiments, it is possible to determine three modes of the overfilling of the filling chamber depending on the piston velocity v_{p1}. It is proven that as the piston velocity v_{p1} increases, the percentage of the gas entrapment in the cast volume also increases, but this phenomenon is not directly proportional to the piston velocity v_{p1}. Critical velocities are determined at which a change in the overfilling mode, or a change in the shape of forming liquid metal wave, characterized by the simultaneous coexistence of two modes, which cause local extrema in the linearity of the gas entrapment increase in the cast volume.

2 Materials and Methods

The influence of the piston velocity in the first phase (v_{p1}) on the formation of a liquid metal wave in the filling chamber of a horizontal high pressure die casting machine was investigated during simulations of the casting cycle in the production of casts according to the Fig. 3.

Depending on the variable value of the piston velocity in the first phase of pressing, in addition to the formation of a liquid metal wave in the filling chamber, gas entrapment in the cast volume was monitored in the places shown in Fig. 1. These places werer chosen with regard to the further mechanical processing of the casts, and thus the possible exposure of poresity during the chip machining. In these places, during the filling of the mold shape cavity, the cores forming structural holes in the cast are circumfluenced. When the cores are circumfluenced, the two streams of melt join together, thus originating the assumption of increased gas entrapment by the melt in the cast volume [14]. Monitoring places are located 3 mm behind the core towards the edge of the cast and 2 mm from the surface of the cast into its volume (Cnx).

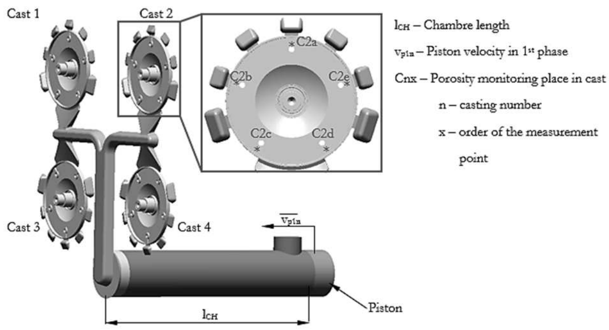

Fig. 3 *Gating system and location of monitoring places*

Numerical simulations performed with the aim of observing the development and formation of the wave of liquid metal in front of the piston face in the filling chamber depending on the piston velocity in the first phase v_{p1} were monitored at 9 different velocities v_{p1n}, which are listed in Tab. 1.

Tab. 1 *Monitored piston velocities in the first phase –* v_{p1_n}

Designation of the observed velocity	$v_{p1\_0.1}$	$v_{p1\_0.2}$	$v_{p1\_0.3}$	$v_{p1\_0.4}$	$v_{p1\_0.5}$	$v_{p1\_0.7}$	$v_{p1\_0.9}$	$v_{p1\_1.1}$	$v_{p1\_1.3}$
Value, ms^{-1}	0.1	0.2	0.3	0.4	0.5	0.7	0.9	1.1	1.3

In order to investigate and assess the shape and development of the liquid metal wave in front of the piston face, it is necessary to consider the dimensions of the filling chamber of the machine and the percentage of the filling of the chamber with melt. The dimensions of the filling chamber, as well as the volume characteristics of the metal dose for one operation, are given in Tab. 2.

Tab. 2 *Dimensional and volumetric characteristics of the filling chamber*

Parameter	Value
Piston diameter d_P, mm	70
Length of the filling chamber l_{CH}, mm	350
Volume of the filling chamber V_{CH}, mm^3	1346275
Dosing volume V_D, mm^3	421890
Filling the chamber, %	31.34

Before the very beginning of the piston movement, the dosage of the necessary amount of liquid metal is included in the filling chamber of the machine. The filling characteristics are listen in Tab. 3. The selected dosing time, as well as the dwell time, is relatively long, taking into account the investigated entity and calming of the free level of the melt before the very beginning of the piston movement.

Tab. 3 *Technological parameters of dosing*

Start dosing	1.0 s after Die close
Filling time / Dosing time, s	5.0
Dwell time, s	3.0
Dosing duration, s	8.0

The development and formation of liquid metal wave in front of the piston face was monitored using the Magmasoft MAGMA 5.4.1 – HPDC module. The setting of the input technological parameters of the casting during the simulation was set in accordance with the setting of the technological parameters of the casting cycle, in which the cast is made in operating conditions (see Tab. 4). The variable parameter is only the piston velocity in the first phase of pressing – v_{p1_n}.

Tab. 4 *Technological parameters of the casting cycle*

Parameter	**Value**
Alloy	EN AC 47100, AlSi12Cu1(Fe)
Pouring temperature, °C	705
Die material	X38CrMoV5_1, DIN 17350
Die temperature, °C	200
Plunger velocity 1st phase, $m.s^{-1}$	v_{p1_n} – see Tab. 1
Plunger velocity 2nd phase, $m.s^{-1}$	2.8
Holding pressure, MPa	25

As reported by Bi, C. et al. [20], to improve the accuracy of the simulation and to obtain a better description of the target entity, networks with higher fineness and high generation efficiency are needed. For simulations performed with the aim of monitoring the development of the liquid metal wave in front of the piston face and the subsequent assessment of gas entrapment in the cast volume, a network was created with a total number of 218,304,072 cells, while the gating system itself is made up of 4,005,475 cells. The network in casts is generated with the cells of size 0.66(X) x 0.33(Y) x 0.66(Z) and the ingate network with the cells of size 0.55(X) x 0.25(Y) x 0.55(Z). Tab. 4 shows the input technological parameters of the casting cycle.

3 Results and Discussion

The results obtained with the help of simulations can be divided into two parts. The first presents a visual assessment of the development and formation of a liquid metal wave in front of the piston face depending on the variable value of piston velocity v_{p1_n}. Subsequently, the proportion of gas entrapment in the casts is evaluated at the locations according to Fig. 3.

3.1 Development and formation of liquid metal wave

With regard to the filling characteristics listed in Tab. 3, the free level of melt in the filling chamber is calmed and its state is expressed by Fig. 4.

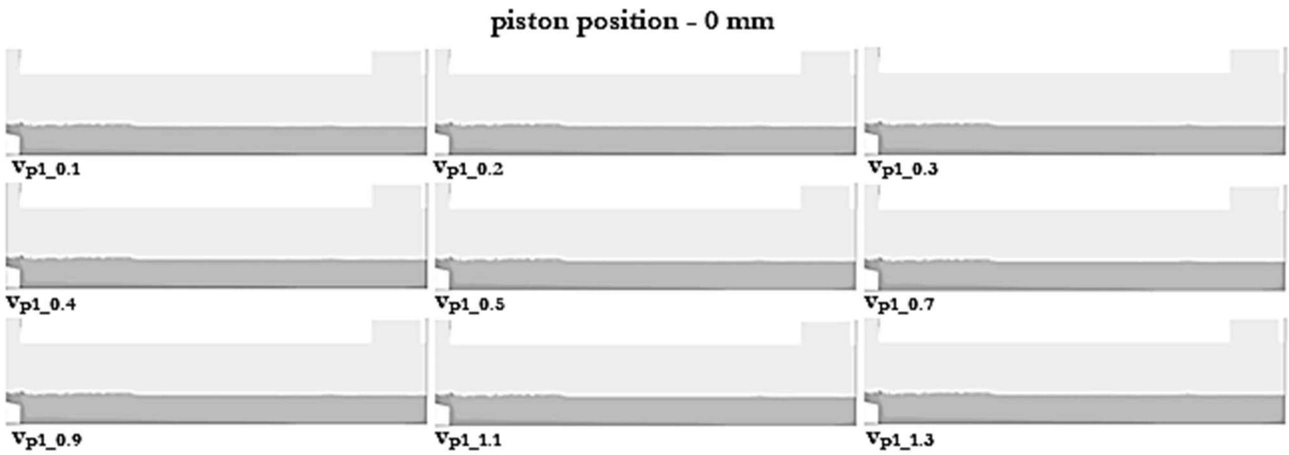

Fig. 4 *Free level of melt before the start of piston movement*

As shown in Fig. 4, before the start of the piston movement, the melt in the filling chamber has a constant character for all variants of setting of the piston velocity in the first phase. Further alignment of the wave development in front of the piston face will be performed in the piston positions significant for that velocity.

The formation of a wave in front of the piston face is noticeable, especially at higher velocities from the beginning of the piston movement. At a piston position of 30 mm (Fig.5) is an obvious differentiation of the wave formation character. It can be assumed that at higher velocities, the wave will roll over the ridge and thereby entrap the gases in the melt volume.

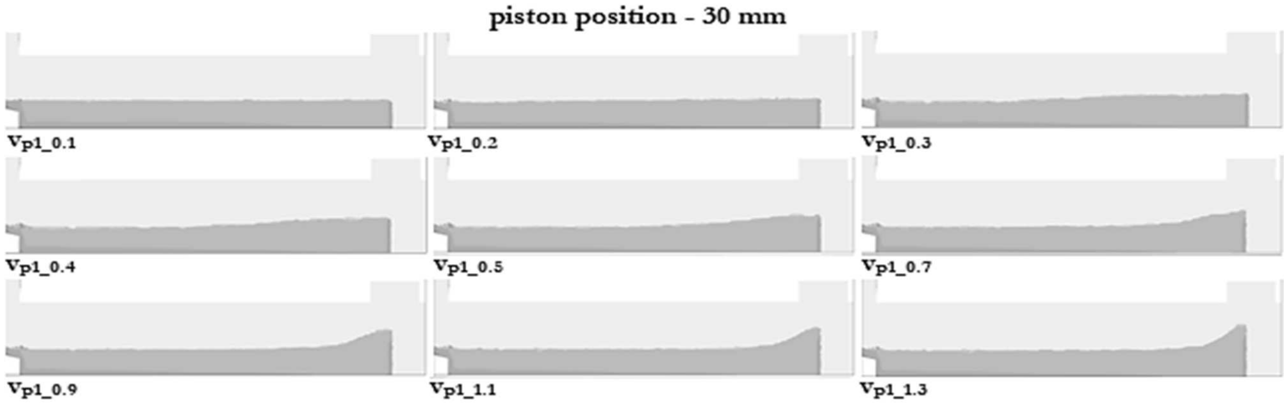

Fig. 5 *Formation of a wave in a piston position 30 mm*

The assumption that was made based on the beginning of the wave formation according to Fig 5 is verified in Fig. 6, where at piston position 100 mm, at the velocity of $v_{p1\_1.3}$, the melt wave begins to roll over its ridge.

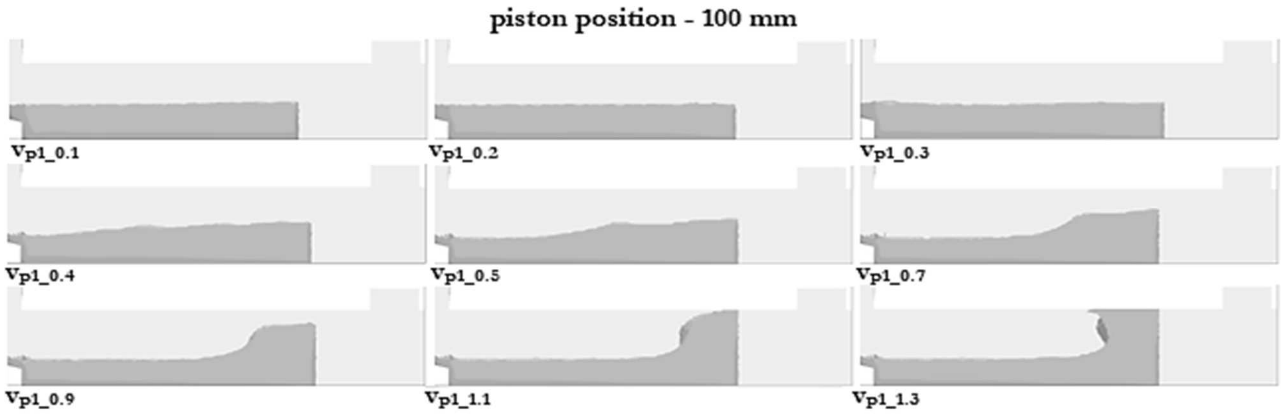

Fig. 6 *Formation of wave in a piston position 100 mm*

Based on Fig. 6 it is clear that at velocities $v_{p1} = 0.1 – 0.3$ m.s^{-1} the free level of the melt is relatively calm in the piston position of 100 mm, at velocities of $v_{p1} = 0.4 – 0.7$ m.s^{-1} the phenomenon of heaving wave of the free level of the melt occurs, and at velocities of $v_{p1} > 0.7$ m.s^{-1} it is obvious that the free level of melt has a tendency to form a wave with the character of rolling over the ridge and entrap gases in the melt volume.

Fig. 7 presents the method of gas entrapment in the melt volume for individual variants of the variable v_{p1}, in the piston position at the time just before 100% of the filling chamber cross-section with the melt.

From monitoring the overfilling of the filling chamber and the sections presented in Fig. 7 arise, that at velocities $v_{p1\_0.1}$ and $v_{p1\_0.2}$ the filling chamber is filled with a calm melt flow without significant turbulence and heaving wave of melt in front of the piston face. The air and gases in the chamber are continuously guided in front of the piston face and above the free level of melt towards the ingate. This mode of filling of the chamber provides a prerequisite for a lower proportion of gas entrapment in the melt volume and their subsequent transport to the cast volume.

The piston velocity $v_{p1\_0.3}$ carries the character of the overfilling mode of the filling chamber at the first positions of the piston as described above, at lower velocities. In the area around the piston position 240 mm, there is a slight reflection of the melt stream from the filling chamber face and thus the gas entrapment in the melt volume is located in the filling chamber in front of the piston face, as demonstrated in Fig. 7.

At velocities $v_{p1\_0.4}$ a $v_{p1\_0.5}$, the phenomenon of gas entrapment in the melt volume in front of the piston face is evident (Fig. 7). This entrapment is

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caused by the reverse movement of the melt in the filling chamber and the formation of a wave resulting from the reflection of the melt stream from the filling chamber face.

The piston velocity $v_{p1\_0.7}$ carries the character of the overfilling mode of the filling chamber in the first piston positions similar to the range of velocities $v_{p1\_0.4}$ a $v_{p1\_0.5}$. When monitoring the overfilling of the filling chamber, it is possible to observe the effort to create a wave in front of the piston face (Fig. 6). Although there is a slight roll over of this wave, the proportion of gas entrapment does not remain under the ridge of the wave (at least not primarily detected), swirling and mixing of the melt and its individual layers occurs, and gas entrapment occurs preferentially in front of the piston face (Fig. 7)

At piston velocities higher than $v_{p1\_0.9}$, the roll over of the liquid metal wave is already obvious. From the increasing piston velocity in the first phase, a more turbulent development and formation of liquid metal wave in front of the piston face is evident, as can be seen from Fig. 5, Fig. 6 a Fig. 7.

Based on the above-mentioned description of the overfilling mode of the filling chamber, it is possible to determine three modes of overfilling and melt flow in the filling chamber. Velocites $v_{p1\_0.3}$ and $v_{p1\_0.7}$ can be characterized as marginal velocities, forming the margins between the individual overfilling modes of the filling chamber.

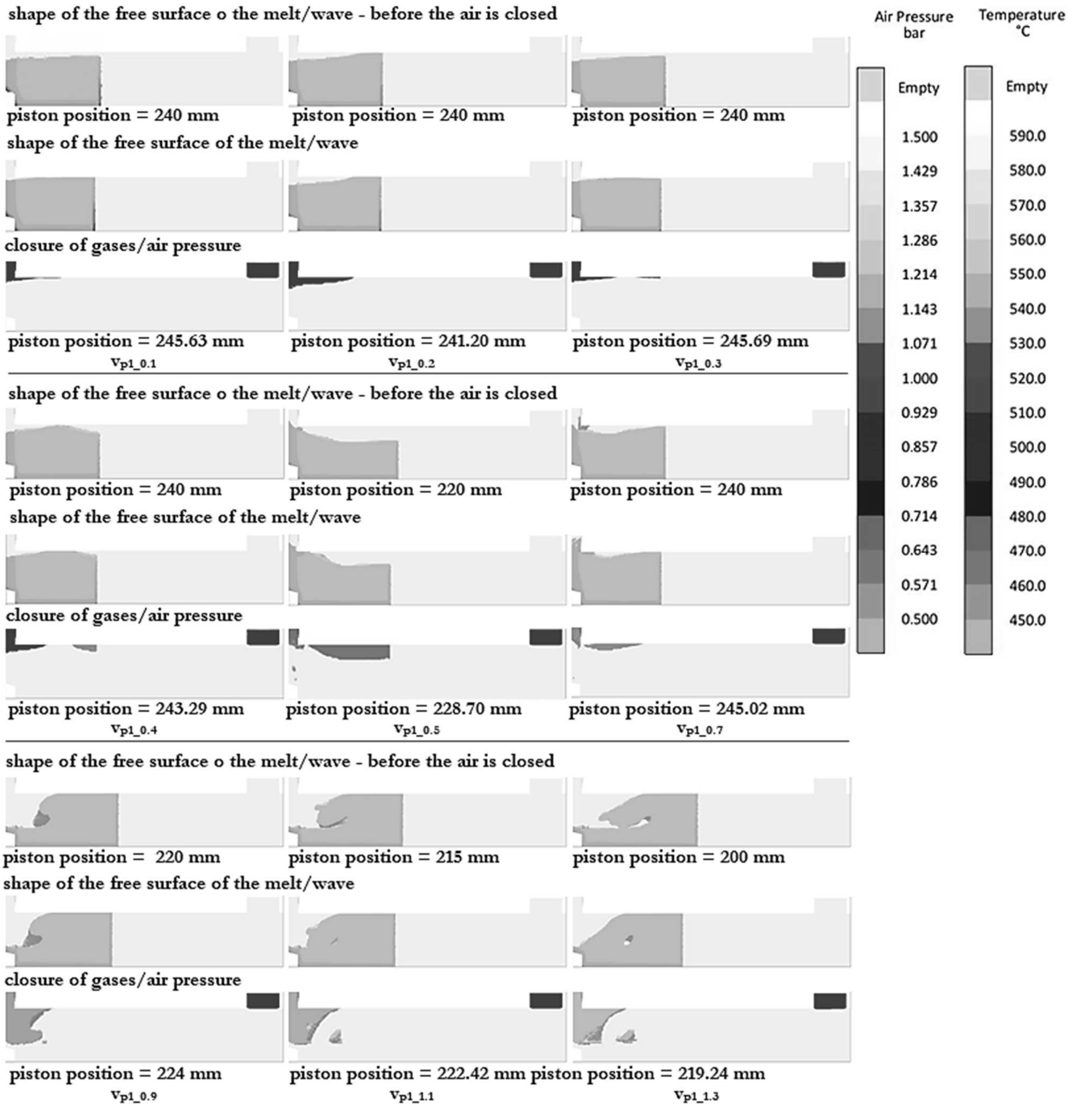

Fig. 7 *Wave formation before and during encapsulation of air in the melt volume*

3.2 Proportion of gas entrapment in the cast volume

The proportion of gas entrapment in the casts volume at the end of the filling phase was evaluated at the monitoring places according to Fig. 3. The evaluation of gas entrapment was performed at the end of the filling phase, when the gating system, including overflows, was filled to 100% of its volume, just before the start of the holding pressure phase. Taking into account the fact that the holding pressure reduces the size and distribution of the pores to a considerable extent ([7][8]), the time selected is the most advantageous with regard to the nature of the monitored entity.

In Tab. 5 the average values of the gas entrapment in the casts volume are shown in the monitored loacations at the variable value of the piston velocity in the first phase.

Based on the values listed in Tab. 5, for a better visual comparison of the detected average values of gas entrapment in the cast, the graph was designed and is presented in Fig. 8.

Tab. 5 *Average values of gas entrapment in the casts volume*

Observed velocity	$v_{p1\_0.1}$	$v_{p1\_0.2}$	$v_{p1\_0.3}$	$v_{p1\_0.4}$	$v_{p1\_0.5}$	$v_{p1\_0.7}$	$v_{p1\_0.9}$	$v_{p1\_1.1}$	$v_{p1\_1.3}$
Value, ms^{-1}	0.1	0.2	0.3	0.4	0.5	0.7	0.9	1.1	1.3
Gas Entrapment, %	0.345	0.449	0.862	0.452	0.743	0.894	0.656	0.878	1.135

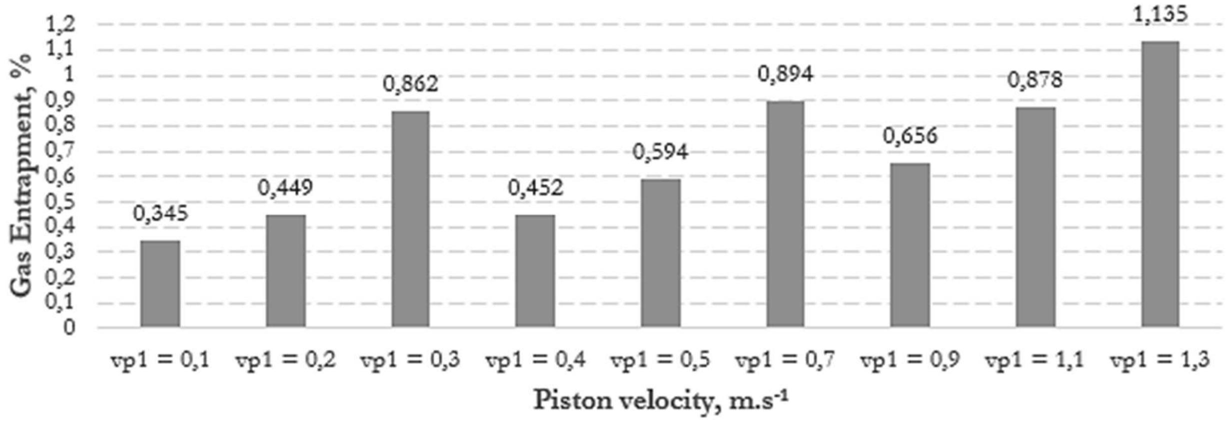

Fig. 8 *Comparison of gas entrapment proportion in cast as a function of variable v_{p1}*

From Tab 5 a Fig. 8 arises that the values of gas entrapment in the casts volume increase, depending on the increasing piston velocity in the first phase. Local extremes in the linear course of the gas entrapment increase in the cast volume are detected at piston velocities $v_{p1\_0.3}$ and $v_{p1\_0.7}$. At these velocities, there is a change in the overfilling mode of the filling chamber, and thus it is possible to assume that the extreme in the linear course is caused by the cumulation of the effect of two simultaneously acting overfilling modes.

4 Conclusion

The paper is devoted to the determination of the influence of the piston velocity in the first phase cast production by high pressure die casting technology with a cold horizontal chamber on the formation of a liquid metal wave in the filling chamber of the machine and on the gas entrapment in the casts volume at the end of the filling phase. 9 different piston velocities were assessed, and the evaluation was performed using the MagmaSoft 5.4. program.

Based on the performed simulations, it is possible to derive three modes of overfilling the filling chamber:

- At low velocities, $v_{p1} < 0.3$ $m.s^{-1}$, the filling chamber is overfilled continuously with calm flow. The free level of melt in the filling chamber does not show swirling and heaving of the melt level, which suppresses the formation of a wave of melt and thus the gas entrapment in the melt volume in the filling chamber;
- At medium velocities, 0.3 $m.s^{-1}$ $< v_{p1} <$ 0.7 $m.s^{-1}$, is the gas entrapment in the melt volume in the filling chamber in the area in front of the piston face. This entrapment is caused by the reverse movement of the melt from the face of the filling chamber and the formation of the melt wave created by the reflection from the face of the filling chamber and moving against the movement direction of the piston;
- At high velocities, $v_{p1} > 0.7$ $m.s^{-1}$, a turbulent heaving wave of melt occurs in front of the piston face, the surface of melt shows the

character of a forming wave already after passing a short path of a piston, and air and gas are entraped in the melt by the roll over of the wave over its ridge;

- Velocities $v_{p1} = 0.3$ m.s^{-1} and $v_{p1} = 0.7$ m.s^{-1}, are determined as marginal velocities, at which the free level of melt in the filling chamber as well as the melt flow regime exhibits the character of two, simultaneously acting flow regimes, which effect cumulates the gas entrapment by melt. This statement is also supported by the fact that local extremes were detected at these velocities in the linearity of the increase of gas entrapment in the volume of casts depending on the increase in the piston velocity in the filling chamber.

According to the above-mentioned knowledge and statements, it is possible to draw these conclussions:

- As the piston velocity in the filling chamber increases, the overfilling of the filling chamber changes from continuous filling with a calm melt level to the development of a turbulent heaving wave in front of the piston face;
- As the piston velocity in the filling chamber increases, the gas entrapment method in the melt volume and their transport to the cast volume changes. At lower velocities, the gases are pushed above the free melt level from the chamber into the gating channels. At high velocities, the gas in the melt volume is confined by the roll over of the melt wave over its ridge;
- With the increasing piston velocity in the filling chamber, the proportion of gas entrapment in the cast volume at the end of the filling phase also increases;
- If a local extreme is shown in the linearity of the increase in the proportion of gas entrapment in the cast volume depending on the increase of piston velocity, it is presumable that at this point there is a simultaneous combination of two modes of overfilling the filling chamber and the culmination of the effect of gas entrapment by the melt.

It is necessary to state that the above-mentioned conclusions are formulated for the filling chamber, which has specific design dimensions and degree of filling (Tab. 2, Tab. 3). First of all, it is necessary to focus on observing the development of the wave and the method of gas entrapment in the volume of the melt at marginal velocities. For this reason, the subsequent works will verify the above-mentioned statements for a chamber with a variable proportion of filling, and with variable structural dimensions both at the marginal velocities and in the entire range of the pressing velocities already defined.

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