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EVALUATION OF CONTINUOUS CASTING OPERATION CONDITIONS BY DIMENSIONLESS, TERNARY MENISCUS PARAMETERS[1]

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Abstract

By means of computer algebra methods, a mathematical model of the thermal processes inside continuous casting moulds can be drawn from the law of energy conservation. The model, named MouldScreen®, analyzes the operating parameters of a given mould and displays the calculated results of all relevant informations, e.g. strand shell thickness, heat flux density, liquid and solid flux film thickness via mouse-click to a computer screen. The model also provides a new classification of the thermal conditions in the meniscus area in form of ternary parameter diagrams. The connections between the different mould parameters, in the form of mathematical equations, lead through normalization transfor-mations to so-called normalization parameters. The dimensionless ratios of these normalization parameters are not dependent on casting speed and they provide a new method of process characterization in particular at the mould level. The constantly rising demands on product quality and operating safety in continuous casting can now be fulfiled by a deeper understanding and thorough analysis of the different physical conditions at the meniscus.

Key words: Continuous casting; Mould flux film; Meniscus area; Ternary meniscus-parameter diagrams; MouldScreen®.

AVALIAÇÃO DE CONDIÇÕES OPERACIONAIS DA FUNDIÇÃO CONTÍNUA POR MEIO DE PARÂMETROS ADIMENSIONAIS TERNÁRIOS DA REGIÃO DO MENISCO

Resumo

Através de métodos de álgebra computacional e tomando como ponto de partida a lei de conservação da energia, foi derivado um modelo matemático dos processos térmicos que ocorrem dentro de um molde de fundição contínua. O modelo, chamado MouldScreen®, analisa os paramêtros de operação de um dado molde e apresenta os resultados calculados para todas as informações relevantes, como por exemplo, para a espessura da casca solidificada, para a densidade de fluxo térmico, para as espessura do filme de fluxante, seja esse sólido ou líquido, tudo por meio de cliques de mouse na tela do computador. O modelo também fornece uma nova classificação das condições térmicas na região do menisco, na forma de diagramas paramétricos ternários. As conexões entre os diferentes parâmetros do molde, na forma de equações matemáticas, conduzem, por meio de transformações de normalização, aos assim chamados parâmetros de normalização. As razões adimensionais desses parâmetros de normalização não são dependentes da velocidade de fundicão e fornecem um novo método para a caracterizacão do processo, particularmente ao nível do molde. As crescentes demandas sobre a qualidade do produto e sobre a segurança operacional nos processos de fundição contínua podem agora ser satisfeitas por meio de um entendimento profundo e de uma análise detalhada das diferentes condições físicas existentes no menisco.

Palavras-chave: Fundição contínua; Filme de fluxante do molde; Área do menisco; Diagramas ternários de parâmetros do menisco; MouldScreen®.

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1 A NEW TOOL IN CONTINUOUS CASTING MODELLING

Since the release of the first computer algebra programme Reduce in 1968, computer algebra (CA) has established itself as a development tool in science and technology in many fields in which mathematical questions are dealt with. Whereas CA very soon became a standard tool in mathematics and physics, numerics remained almost without excep-tion Number One on the hit list of mathematical calculating methods in engineering science disciplines. The reasons lie on the one hand in the complexity of the tasks and the clearness of numerical results and on the other hand also in the dread of abstract mathematical-analytical solutions.
The description of the physical phenomena in the inside of a continuous casting mould also fit into the category of complex tasks that are often dealt with by means of numerical methods. Alongside the aspects of fluid dynamics and heat flux from the inside to the outside of the mould, phase transitions and the inclusion of temperature-dependent material properties of the steel, the casting powder or the casting flux, the ma-chine components and the cooling water etc. all have to be taken into consideration. At first sight it seems hopeless to try to reach a compre-hensive physical-mathematical description, because these processes are also interlinked. In addition there is the influence of mould oscillation and the formation of oscillation marks. The existing continuous casting models are therefore usually limited to partial aspects of continuous casting such as fluid flow, solidification, microstructure, segregation, non-metallic inclusions or slag infiltration, and they conflate the resulting partial models to a model package.
Analytical and semi-analytical models or a combination of analytical models with empirical approaches are put forward for example in Cicutti and Boeri,[1,2] Paul,[3] DiLellio and Young,[4] Wünnenberg,[5] Chiang,[6]Jeschar and Specht,[7] Bland,[8] Larrecq, Saguez and Wanin,[9] Singh and Blazek,[10] Miyazawa e Muchi,[11] Mizikar,[12] Hillls[13] and Roth.[14] Semi-analytical simulation calculations on slag infiltration which are particularly interesting for this paper were carried out by Yamauchi, Emi and Seetharaman[15] and Mörwald, Steinrück and Rudischer.[16] One of the few models on the subject of continuous casting combining analyti-cal approaches, series expansions and empirical considerations was published by DiLellio and Young.[4] Their asymptotic, one-dimensional model of the thermal conditions in the mould and the flux film of conti-nuous steel casters reflects in the main the results of the present paper. The algorithms and parameter studies described in Wosch,[17,18,20,210] and Wosch and Hilgenhöner[19] derive solely from a model developed using CA methods.
New tools open up new possibilities: one only has to apply them in order to arrive at new insights. If one limits the problem first of all to simplified geometry and constant material properties, then the application of stan-dard mathematical methods leads to useful analytical approximations. These analytical approximations then form the basis of further considera-tions. The inclusion of temperature-dependent material properties or location- and time-dependent parameters is indeed possible by means of differentials of approximation in iterative algorithms. In the case of the continuous casting mould, the integral and differential formulation of energy conservation provide for example the progression of isotherms in the strand shell and the location-dependent flux film thickness between mould copper plate and strand.[19]

2 ANALYTICAL APPROXIMATION

To solve the energy balance equation in plane geometry, there must be a restriction to the two main coordinates. The x-axis runs along the slab surface from the meniscus to the mould exit. The y-axis is directed into the slab center. The point of origin lies at the mould level. The material properties are regarded as constant to start with. After transformations, the following equation results:

$$\frac{\rho\, c_p\, v_c}{\lambda}\left(\frac{\partial}{\partial x}T(x,y)\right)-\left(\frac{\partial^2}{\partial y^2}T(x,y)\right)=0 \qquad (1)$$

Details of this see Wosch.[17] Under boundary conditions, this type of partial differential equation has the following formal solution if the temperature in the meniscus is constant (e.g. the same as the liquid or solid tempera-ture) and if the energy resulting from overheating and solidification is conducted through the strand shell to the cooling water:

$$T(x,y)=a_1+a_2\mathrm{erf}\left(\frac{a_3+a_4 y}{\sqrt{a_5+a_6 x}}\right) \qquad (2)$$

In this case, the constants ai are dependent on the operating parameters of the mould and must be determined from the boundary conditions. Equation 2 is described as an analytical approximation. Temperature-dependent material properties can be included on the basis of the diffe-rentials of the solution in iterative algorithms. Details of this calculation method are given elsewhere[18] and are not to be dealt with here. For the liquidus- or solidus isotherm, here named s(x), one arrives at the following formula:

$$\frac{s(x)}{p_s}=\left(\sqrt{1+\frac{x}{p_x}}-1\right) \qquad (3)$$

Thus the thickness of the strand shell in the casting mould grows like a square root function, irrespective of the value of the two parameters p_s and p_x.

3 SCALING NORMALIZATION

On the basis of Equation 3 it also becomes evident that only two num-bers are necessary to describe the thickness of the strand shell as a function of the location in any slab or thin slab casting mould in the first approximation: ps and px. These two parameters are unified in one length and serve as natural scalings for location coordinates and strand shell thickness in the syntax of Equation 3. One can designate them henceforth as normalizing parameters. If one now identifies the following:

$$\frac{x}{p_x}=x_N \quad \text{and} \quad \frac{s(x)}{p_s}=s_N \qquad (4)$$

then all strand shell thicknesses lie on a normalized curve, which results from the analytical approximation:

$$s_N = \left(\sqrt{1+x_N} - 1\right) \tag{5}$$

The functional relation conveyed by Equation 5 would hardly be worth mentioning if the normalization were only applicable to the strand shell thickness. However, it can also be transferred to all the other important location dependent parameters, such as for example the local heat flux density, the heat transfer resistance of the flux film, the water tempera-ture in the cooling water channels, the temperature field in the strand shell, and the integral heat flux density or the cooling water ΔT.
In this new syntax all location dependencies are depicted by just a few types of analytic functions. The decisive role in characterizing the pro-cess is therefore no longer played by the solution of partial differential equations but by the normalizing parameters of the resulting functions. The local heat flux density for example can be described as follows:

$$q_N = \frac{1}{1+s_N} = \frac{1}{\sqrt{1+x_N}} \tag{6}$$

The heat transfer resistance in the flux film, here denoted by GP in allusi-on to the word 'Gießpulver' (German for casting powder), also becomes quite manageable in the normalized syntax:

$$GP_N = \frac{1}{q_N} = 1+s_N = \sqrt{1+x_N} \tag{7}$$

It is particularly interesting in this context that the normalized integral heat flux density IQ_N is identical to the normalized temperature difference of the cooling water, ΔT_N:

$$IQ_N \equiv \Delta T_N \tag{8}$$

Altogether, using computer algebra methods it has been possible to identify eight independent normalizing transformations and the corres-ponding normalization parameters, which can be subdivided into four groups on the basis of the physical units of the parameters.

Table 1. Normalization parameters of the analytical approximation

	Unit	Range	Explanation
p_x	m	0,01 to 0,5	x-axis
p_S	m	0,001 to 0,01	y-axis
p_q	W/m²	$4 \cdot 10^6$ to $3 \cdot 10^7$	Local Heat Fux
p_{IQ}	W/m²	$2 \cdot 10^5$ to $2 \cdot 10^6$	Integral Heat Flux
p_W	K	1 to 15	Water Temperature
p_T	K	800 to 1200	Strand Shell Temperature
p_K	m²K/W	$3 \cdot 10^{-7}$ to $9 \cdot 10^{-6}$	Heat Transfer Resistance
p_{GP}	m²K/W	$2 \cdot 10^{-5}$ to $5 \cdot 10^{-4}$	Heat Transfer Resistance of Fux Film

In Table 1 the eight parameters are summarized in symbols with their ranges. The most important point is that the normalization transforma-tions cause a separation of

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the location-dependent quantities into two components: a mathematical function valid for all casting moulds and an individual value for every operating condition. The thermal condition of any continuous slab casting mould is thus no longer specified by the individual function progression e.g. of the local heat flux density, but by a single figure characterizing the local heat flux density plus its physical unit.

4 DIMENSIONLESS MENISCUS PARAMETERS

In addition to the strand shell thickness, the heat flux density, the heat transfer into the cooling water and the thickness of the flux film between copper plate and strand, the MouldScreen® programme[19] also calculates the normalization parameters mentioned in Table 1. They are deter-mined in the framework of an automatic data evaluation from the input parameters of the model. There are now computation results for many thousands of operating conditions in very diverse slab and thin slab plants, and these form a basis for statistical investigations. From these statistical investigations it follows that the three of the four dimensionless ratios given in Equation 9 form Gauß distributions around certain values identical for all casting moulds.

$$V_1 = \frac{p_x}{p_s}, \quad V_2 = \frac{p_w}{p_T}, \quad V_3 = \frac{p_K}{p_{GP}} \qquad (9)$$

The three quantities V_1 , V_2 and V_3 describe the thermal conditions in the mould level and form the basis of further observations. The fourth ratio (p_q/p_{lQ}) includes the mould length and describes the thermal conditions at the casting mould exit. To give a comparative representation of the sta-tistical distributions of the V_i, these are transformed into the value range between 0 and 1 (Equation 10). Figure 1 shows the resulting fre-quency distributions.

$$n_1 = \frac{V_1}{\sum_{i=1}^{3} V_i}, \quad n_2 = \frac{V_2}{\sum_{i=1}^{3} V_i}, \quad n_3 = \frac{V_3}{\sum_{i=1}^{3} V_i} \quad \text{with:} \ \sum_{i=1}^{3} n_i = 1 \qquad (10)$$

It can be demonstrated that the frequency distributions shown in Figure 1 are in fact Gauß distributions. The values of n_i thus form random distri-butions around characteristic mean values (m_1 = 0.07923; m_2 = 0.78123; m_3 = 0.13954). In this context it is particularly interesting that these mean values are not dependent on the casting speed. The casting speed range evaluated lies between 0.24 m/min and 6.6 m/min. It therefore covers slab and thin slab casters.

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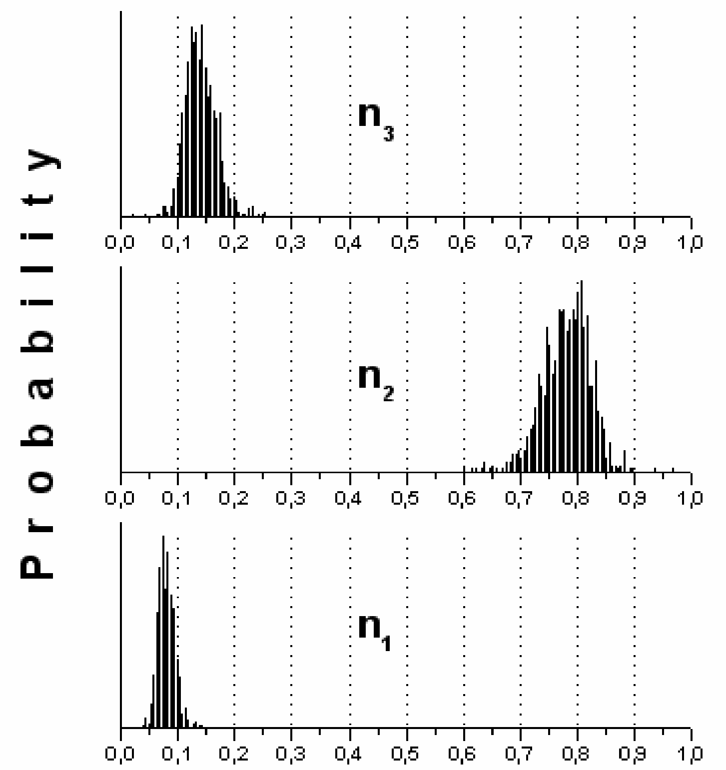

Figure 1. Frequency distributions of normalizing parameters n_i.

5 TERNARY DIAGRAMS

A new method for classification of the operating conditions of continuous casting moulds now follows from the above statistical observations. This means that one can describe the thermal conditions in the mould level of any continuous casting machine by three non-dimensional numbers. They are known as ternary meniscus parameters. A ternary plot of the normalizing parameters n_i for about 1000 slab and thin slab data is given in Figure 2. Outstandig is the asymmetrical location of the points of state in the upper corner of this diagram.

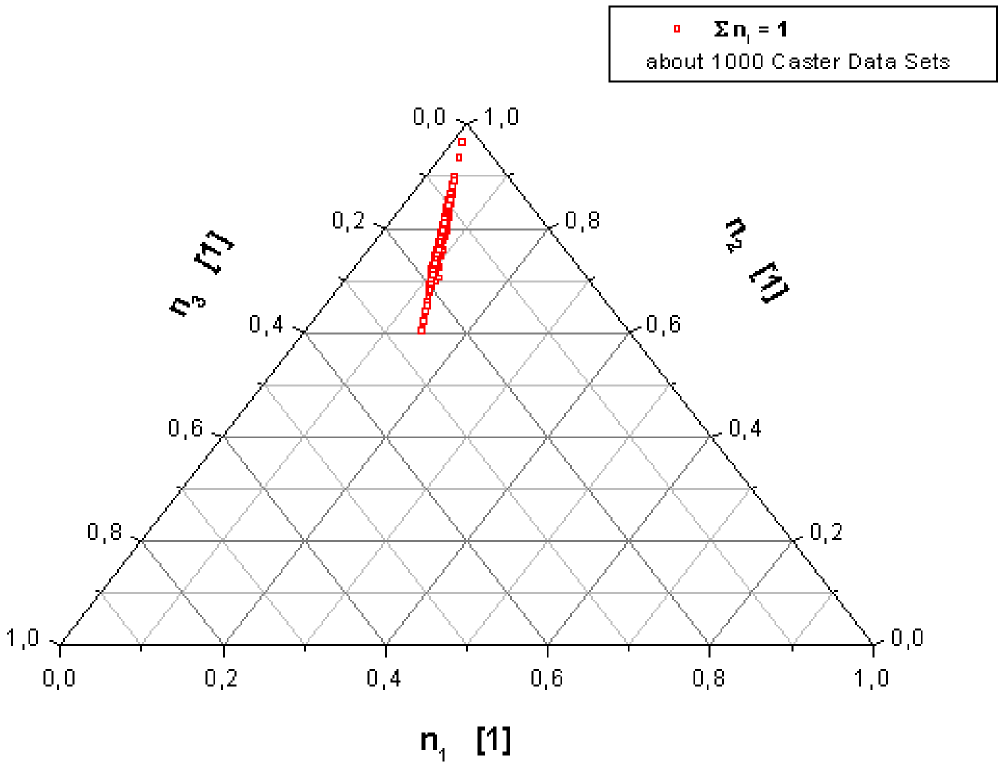

Figure 2. Ternary Diagram of the original normalizing parameters n_i.

If one multiplies the dimensionless ratios V_i with uniform factors $ß_i$:

$$\beta_i = \frac{1}{m_i \sum_{j=1}^{3} \frac{1}{m_j}} \tag{11}$$

and redefines the corresponding normalizing parameters, a set of new formulae for symmetrical quantities p_1, p_2 and p_3 result::

$$p_1 = \frac{\beta_1 V_1}{\sum_{i=1}^{3} \beta_i V_i}, \quad p_2 = \frac{\beta_2 V_2}{\sum_{i=1}^{3} \beta_i V_i}, \quad p_3 = \frac{\beta_3 V_3}{\sum_{i=1}^{3} \beta_i V_i} \quad \text{with}: \sum_{i=1}^{3} p_i = 1 \tag{12}$$

The parameter p_1 is determined largely by the steel properties, p_2 is given by the mould design and cooling, and p_3 consists of the flux film properties. In symbolical syntax this is described in the notations in Equation 13.

$$\begin{aligned} p_1 &= f(\text{Steel Properties}) \\ p_2 &= f(\text{Mould Design and Cooling}) \\ p_3 &= f(\text{Casting Powder Properties}) \end{aligned} \tag{13}$$

By entering these p_i in a similar ternary diagram like Figure 2 one gets Figure 3 which exhibits a symmetry with respect to the vertical centre line. The graph includes the ternary meniscus parameters of approximately 3000 data sets, both from slab and from thin slab casters.

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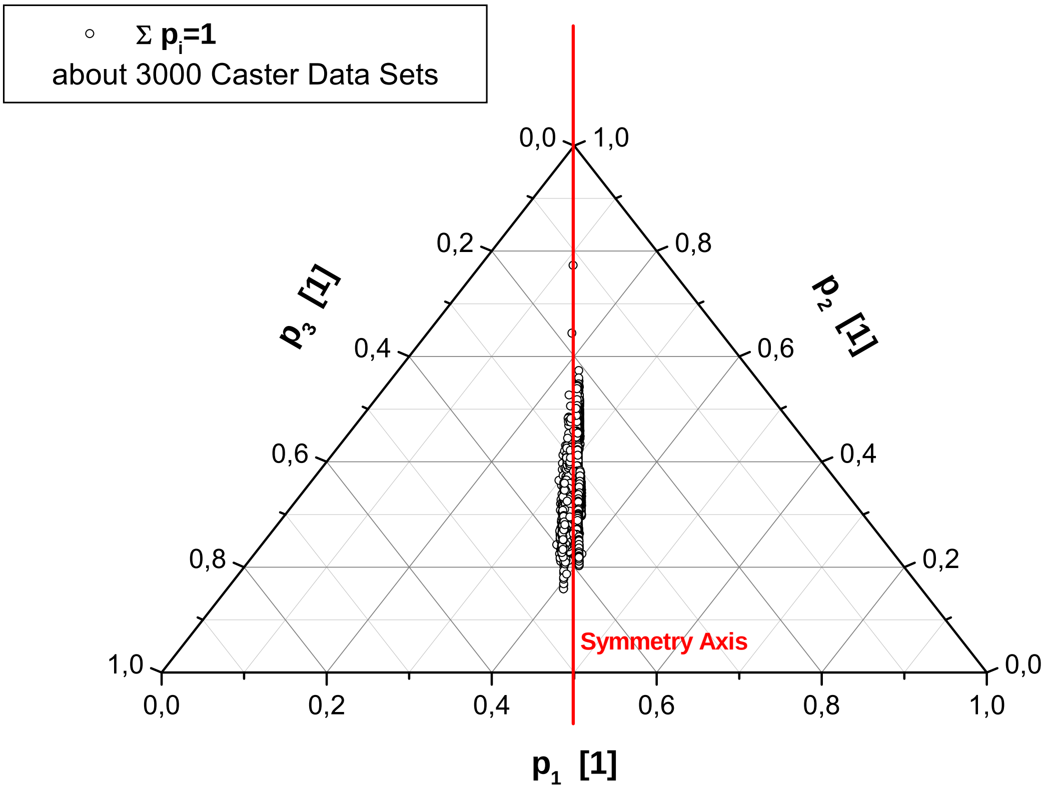

Figure 3. Ternary diagram of the three non-dimensional meniscus parameters p_1, p_2 and p_3 , approx. 3000 caster data sets.

As the points of state in the ternary meniscus parameter diagram follow the vertical symmetry axis the highest concentration of points is reached at the centre with $p_1 = p_2 = p_3 = 1/3$. The statistical scattering around the symmetrical axis in Figure 3 is quite small. This indicates that there is a mathematical correlation between p_1, p_2 and p_3:

$$\begin{aligned} p_3 &\approx p_1 \\ p_2 &\approx 1 - 2p_1 \end{aligned} \qquad (14)$$

This means that in reality only one single parameter is required to characterize the thermal conditions in the meniscus. In Figure 4 this single parameter is denoted by the symbol w. Its range of values lies between zero and infinity. In the centre of the ternary diagram it has the value of w = 1. Figure 4 shows a cluster of points around the region of 0.9 < w < 1.1. This cluster of points in the centre of the ternary diagram also includes operating conditions in both slab and thin slab casters.

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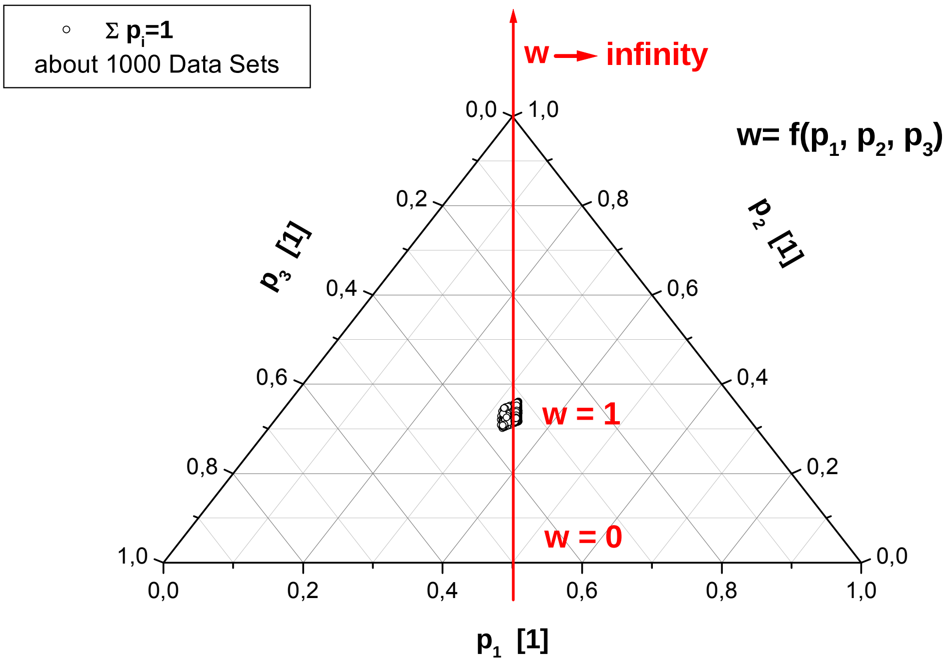

Figure 4. Selection of 1000 central range points of the ternary non-dimensional meniscus parameter diagram including slab and thin slab data.

Whether optimum casting conditions exist in the centre of the ternary meniscus parameter diagram is the subject of present research. To find this out, it is necessary to form a relation between the location of the state points in the ternary diagram and the quality characteristics of the product or the terms of save casting. Abnormal operating conditions betray themselves by their location in the ternary diagram. This concept is demonstrated in Figure 5, where the state points of a sticker event in the ternary meniscus parameter diagram are given.

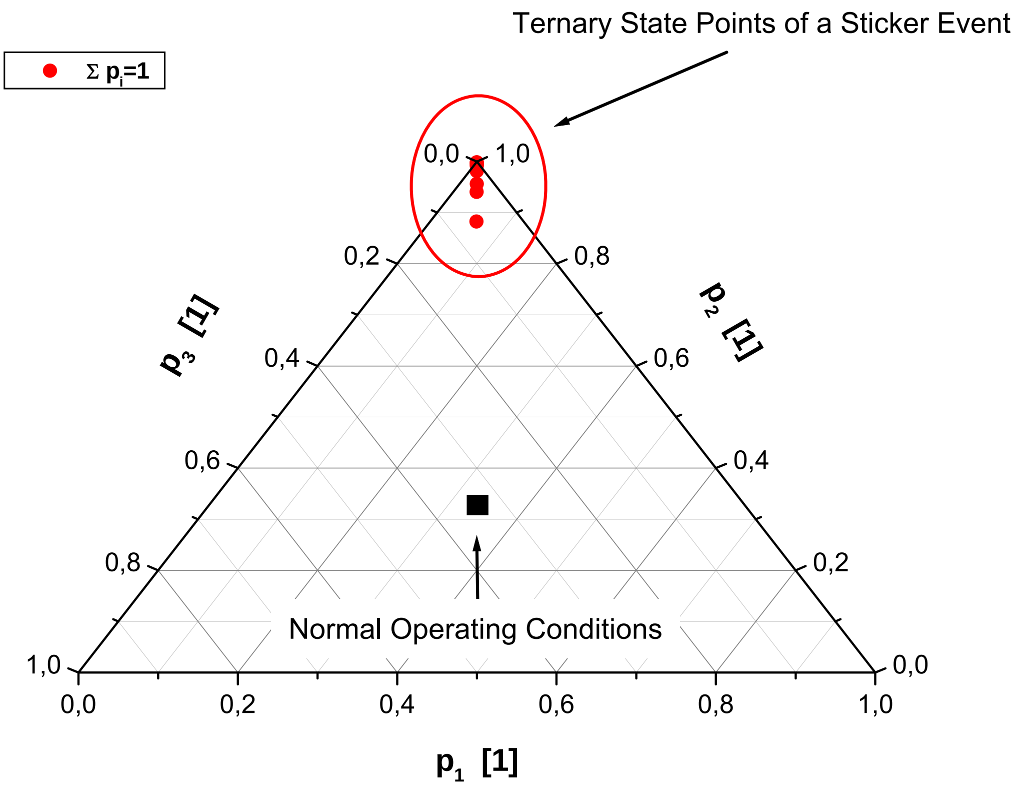

Figure 5. State points of a sticker event in the ternary diagram.

6 CONCLUSIONS

By means of computer algebra methods, a mathematical model in the form of analytical approximations can be drawn from the law of energy conservation. The correlations between different physical parameters, in the form of mathematical equations, lead through normalization trans-formations to normalization parameters. This causes a separation of the location-dependent quantities into two components: A few mathematical functions valid for all casting moulds and a set of normalizing parameters for the individual operating conditions. The dimensionless ratios of these normalization parameters are not dependent on casting speed and they provide a new method of process characterization in the region of the mould level, in the form of ternary diagrams. This abstract view of conti-nuous casting by analysis of analytic functions and individual normaliza-tion parameters provide a deeper understanding of the different process conditions.

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