Mathematical modelling for the design of continuous casting machines

The use of mathematical models, accurately calibrated with experimental data are key to the design of modern continuous casting machines, optimising the casting process and determining equipment status. Uralmash – Metallurgical Equipment Ltd has a suite of such programs, which are described here.

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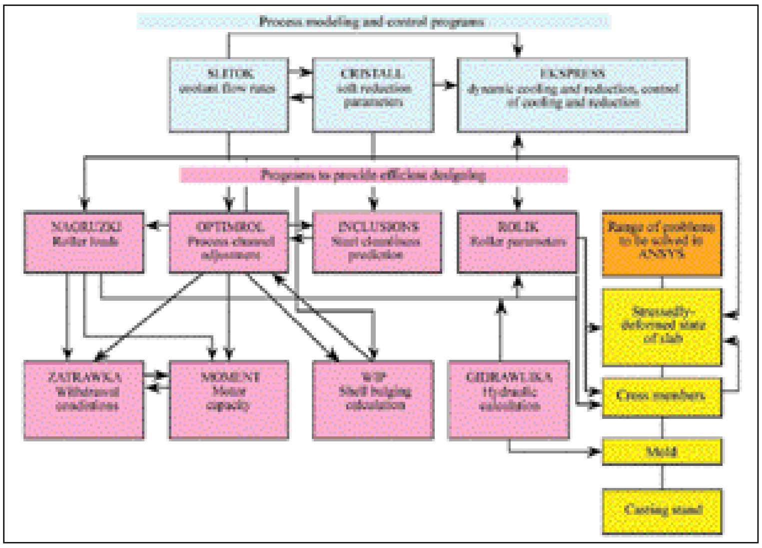
Uralmash – Metallurgical Equipment Ltd is the Russian leader in the field of design and manufacture of continuous casting machines (CCMs). At present, 70 slab casters developed by the company operate in many countries, including Japan, Finland, Yugoslavia, Egypt, Algeria, Bulgaria, Hungary and Pakistan. In 2002-03 two four-strand slab Uralmash-designed CCMs were commissioned at Magnitogorsk Steel Works, Russia, each of 3.5Mt capacity, the highest in Russia (see *Table 1*).

The design and quality of CCMs, including steel preparation for casting, design of an efficient process channel through application of advanced continuous casting practices and quality control, is key to efficient continuous casting.

A software package called MNLZ has been developed to aid machine design and to model the processes, control systems and equipment status, allowing new technological and design solutions to be found on the basis of numerical analysis.



● **Figure 1** ***MNLZ calculation package. Software communications diagram***

Casting speed, m/min	Ladle capacity, t	Number of strands	Slab size, mm	Basic radius, m	Metallurgical length, m
1.2	350	4	250*1,250–1,350	8	28

● **Table 1** ***Slab CCM, Magnitogorsk Steel Works specification***

Modelling of casting process and equipment status

The MNLZ software package is based on more than 30 years' experience in design and experimental studies of CCMs, and is used to model the continuous casting process and to perform calculations of parameters which characterise the slab formation process and the CCM equipment status. These are: strand shell thickness, temperature characteristics, coolant flow rates, coolant pressure and pressure drop, stresses, strains, indices characterising formation of defects in a slab, and equipment longevity.

The package includes the latest calculation techniques and theoretical representation of the processes occurring in the two-phase zone of the strand under solidification. The new technologies of dynamic control of secondary strand cooling and soft reduction of the strand in the two-phase state, which were developed to improve the quality of continuously cast slabs and longevity of the CCM equipment, are also included. These models are closely bound and interact with programs developed to calculate efficient design parameters of the CCM equipment. There is a close relationship between these calculation package programs, in that a calculation made using the process programs allows production of initial data for the programs which support efficient design, and vice versa (see *Figure 1*).

For example, in the case of solving a problem of profiling a process curve and of selecting the roller pitch, the most important initial parameters are the slab shell thickness and temperature distribution in the cast slab, which, in turn, influence management of the specific CCM. Selection of the roller pitch, for example, determines the division of secondary cooling zones and management of cooling as applied to a specific design.

An important component for management of the automated CCM design is the use of experimental support. For example, to model the strand solidification process and to control coolant flow rates on the basis of bench test results for nozzle units, their thermal and flow rate characteristics are determined and are used as initial data for the calculations of the solidification process and control of coolant flow rates. Similarly, experimental measurements carried out using the frozen-in thermocouple method or pyrometric method, allow calibration of the mathematical models, so improving their accuracy.

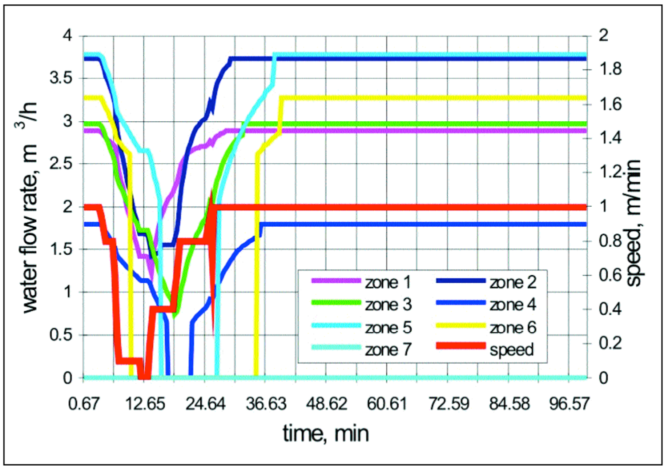
The company devotes close attention to the analysis of calculated and experimental results using statistical methods. The latter are a part of the package approach to the problem of organising a thorough calculation support system for the design process, which is underpinned by mathematical planning of experiments and management of a quality control system.

Modelling of the cast slab formation process

This is based on two programs: SLITOK and CRISTALL. The SLITOK program was developed on the basis of a quasi-equillibrium solidification model to simulate the formation process of a travelling slab. The program is designed to calculate the temperature, shell thickness and location of the crater end (solving a direct problem with boundary conditions of type 1, 2 and 3). These are respectively, temperature, heat flow rate in the mould, and heat transfer factor in the secondary cooling zone and coolant flow rates (solving a problem with boundary conditions of type 2 in the mould and type I in the secondary cooling zone). When solving the problem of thermal profiles the temperature change of the broad face along the process axis, or coolant flow rates can be given. Flow rates are evaluated in the heat transfer coefficient values for the cooling zones on the basis of regression relationships established according to the results of the nozzle unit bench tests and experiments.

The SLITOK program provides the most important initial data on temperature and shell thickness for virtually all the programs intended to calculate an efficient design of a CCM. It also supports the establishment of process manuals on coolant flow rates, programming of PLCs of the automatic control system, level I, and also establishment of a control algorithm of dynamic flow rate regulation for the coolant flow rate control system, level II.

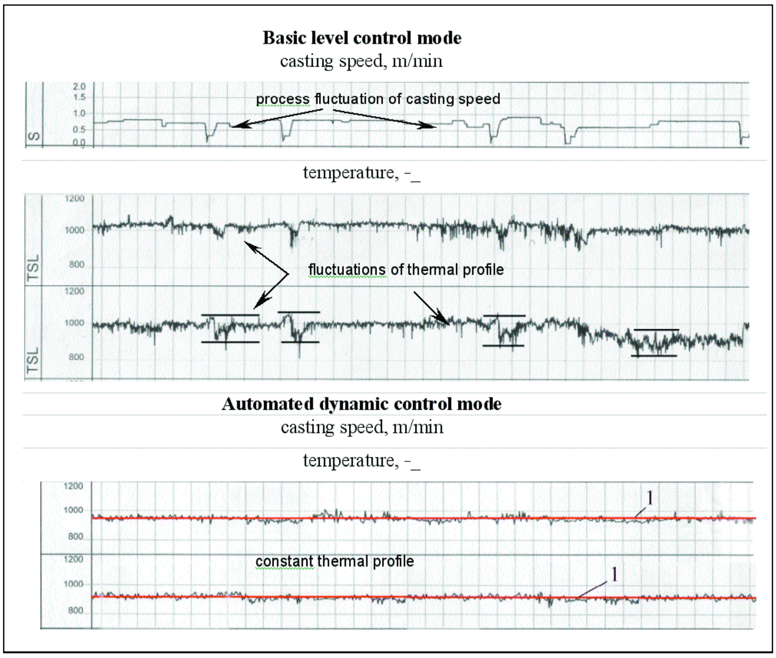
The CRISTALL program is based on the two-phase zone theory (heat conductivity, diffusion, continuous flow and momentum conservation equations in two dimensions), and models the soft reduction process. The program is applied to calculate the soft reduction parameters; namely, soft reduction zone limits, melting speed, hydrodynamic pressure, and pore and carbon contents of approaching of solidification fronts under soft reduction. Both programs support establishing of the EKSPRESS control algorithm.



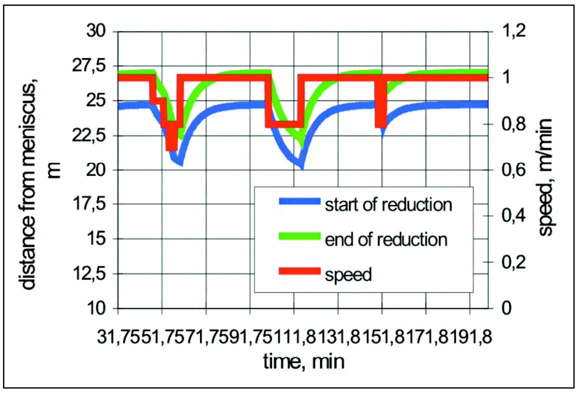
● Figure 2 ***Water flow changes by zone, depending on casting speed***

Dynamic cooling and soft reduction

The EKSPRESS program includes two modules: dynamic control of flow rates in the transient modes with the aim of stabilising the thermal profile, and a module for tracking the crater end and control of hydraulic cylinder operation in the soft reduction unit. Unlike a similar well-known system, DYNKOOL by Rautaruukki, the EKSPRESS program not only includes options, such as registration of liquid steel overheating, heat removal in the mould and casting speed modes, but in addition, tracks the travel of a strand zone overcooled below the mould under casting at reduced speed and takes into account the cold start factor, i.e. it specifies reduced coolant flow at the beginning of a casting sequence, when the equipment has not reached a stable state. The EKSPRESS functions in the automatic process control system and is directly linked with control of the continuous casting practice and slab quality improvement. In case of CCMs delivered without any soft reduction unit, the EKSPRESS includes a single module of dynamic control of coolant flow rates. *Figure 2* shows functioning of this module.



● **Figure 3** ***Comparison of water flow rates controlled from basic (blue) and automated levels (red) at CCM No.3, Magnitogorsk Steel Works***



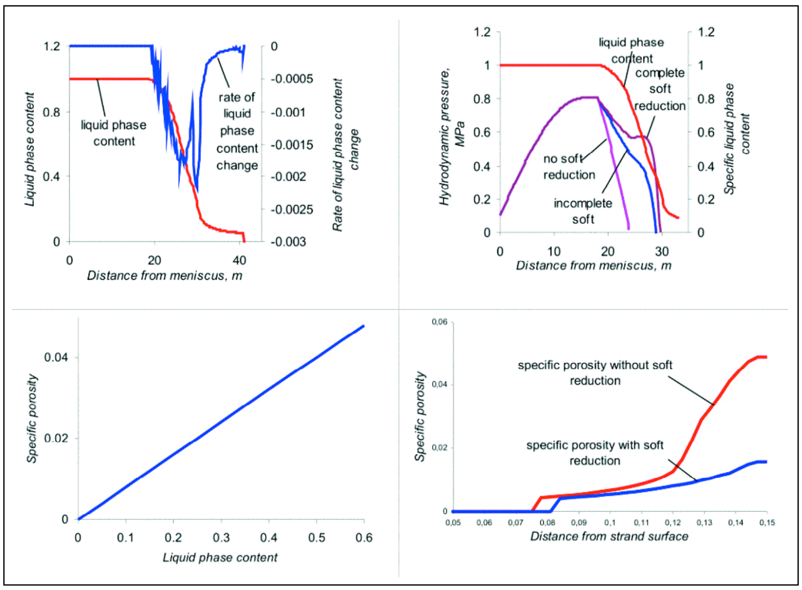
● **Figure 4** ***Location of soft reduction zone limits depending on casting speed***

The solidification history registered under dynamic control of coolant flow rates allows a stable temperature profile to be maintained even with variable casting speed modes and slab overheating or overcooling, which is inevitable if flow rate is proportional to the casting speed. *Figure 3* shows the efficiency of the EKSPRESS module functioning at CCM No. 2, Magnitogorsk Steel Works.

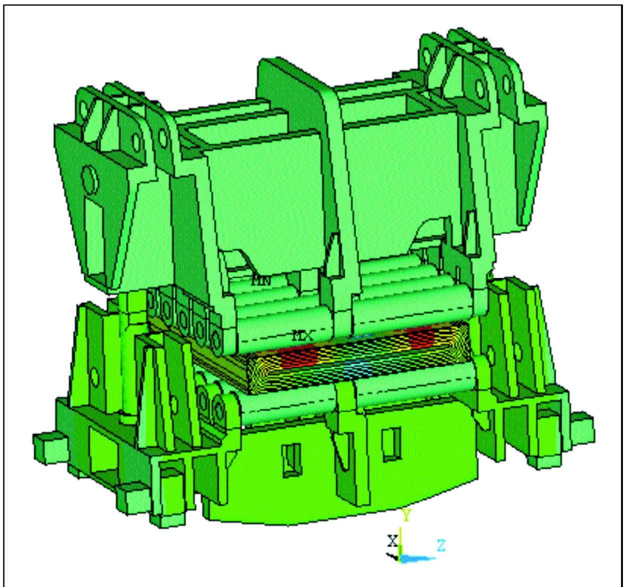
In the case of CCMs delivered with a soft reduction unit, EKSPRESS also includes a module for tracking of the crater end, control of hydraulic cylinders in the soft reduction unit and prediction of impurity and pore contents. *Figure 4* shows tracking of the crater end in the variable casting speed mode, which is implemented from level 2 of the hydraulic cylinder control operation in the soft reduction units. At level I PLCs store data on roller gap settings of the soft 'wedge' reduction unit rollers.

To calculate the settings using the CRISTALL program, the approaching values of solidification fronts are calculated to maintain a positive hydrodynamic pressure 'P' of the melt during the slab contraction process. *Figure 5* shows the results of modelling of strand solidification with and without soft reduction. It can be seen from the diagrams that reduction of the strand in the solidification zone end results in increased hydrodynamic pressure of the melt in the two-phase zone and accordingly, in the reduced content of liquid phase under P=0 (b), resulting in the reduced specific pore content along the thermal axis of a slab after complete solidification (c), and over the slab cross section (d).

However, if the solidification front approaching value is critical for management of proper hydrodynamic function



● **Figure 5** ***Results of calculation modelling for strand solidification with and without soft reduction***



● Figure 6 ***Spectrum of movements for the soft reduction unit strand system***

of the soft reduction units, then accurate actuation of the hydraulic cylinders providing the roller gaps is required. These values can essentially differ from the front's approaching values and essentially depend on the slab shape and size. The gap settings are calculated using the ANSYS multipurpose calculation package in contact definition. A solid-state model of the roller unit with the strand in a two-phase state is established in the CAD-program of SolidWorks. This model is used initially to establish a finite-element model where the mechanical properties vary depending on the temperature, deformation velocity and chemical composition of steel to be cast. *Figure 6* shows the spectrum of movements for the soft reduction unit strand system.

During the commissioning period the settings are updated according to the template analysis results, and the mathematical model is calibrated with the updated control algorithm.

Summary

Uralmash – Metallurgical Equipment Ltd uses a modular approach to manage the design process, based on thorough mathematical modelling of the whole system of interactions of a cast slab with the CCM equipment. We are able to implement the complete scope of engineering, including selection of basic data on CCM design, detailed engineering of individual units of the machine including development of new processes, automated control of these processes during operation and quality control.

In its design developments Uralmash – Metallurgical Equipment Ltd collaborates with Russian companies, such as Data Center and TECHNOAP, as well as foreign companies, such as Corus, Rexroth, Siemens and Vesuvius in the UK and Germany. We are ready to further extend collaboration with metallurgical and engineering companies worldwide.

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