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Computer Simulation and Optimization of VOD Treatment

Računalniška simulacija in optimiranje VOD obdelave

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Mathematical model and the software CAPSS (Computer Aided Produc tion of Stainless Steel) developed as a part of URP-C2-2566 research program were used for computer simulation of EAF-VOD-CC stainless steelmaking technology line. Basic aim of model testing was to optimise VOD treatment with emphasis on obtaining the maximum productivity at the lowest possible thermal load of VOD ladle and EAF tap temperature. It was concluded that only computer controlled oxygen blowing can secure maximum productivity at the acceptable thermal load of VOD ladle and lowest EA furnace tap temperature.

V okviru petletnega raziskovalnega programa URP-C2-2566 izdelani model in računalniški program CAPSS (Computer Aided Production of Stainless Steel) je bil uporabljen za računalniško simulacijo EOP-VOD-KL tehnologije za izdelavo nerjavnih jekel. Osnovni namen modelnih poskusov je bil optimiranje VOD obdelave s posebnim poudarkom na zagotavljanju maksimalne produktivnosti VOD naprave ob najmanjši možni toplotni obremenitvi VOD ponovce in minimalni temperaturi preboda. Ugotovili smo, da le računalniško programirano pihanje zagotavlja maksimalno produktivnost ob še sprejemljivi toplotni obremenitvi VOD ponovce in minimalni temperaturi preboda.

1 Introduction

The production in metallurgical industries was for a very long time based dominantly on experience. However, the development of theory of metallurgical processes and metallurgical thermodynamics coupled with small-size and yet powerful computers has made it possible to combine the experience with theoretical knowledge, which can result in a significant improvement of operation performance and raising techno-economic production parameters to an essentially higher level.

The application of computers in steelmaking has become indispensable due to high competition and ever increasing demands for lower price, better quality and narrower tolerances of steel properties such as strength, ductility, hot and cold deformability, chemical composition, corrosion resistance, etc. The concept of TQC (Total Quality Control) which excludes any refuse is based on absolutely reliable control of quality. At present TQC is obligatory for all high priced products. Consequently, it is imperative also in the manufacture of stainless steel since the value of a heat of high quality stainless steel can amount up to 300,000 US$. Naturally, there is no room for any allowable refuse despite the fact that technological regulations at present recognize allowable waste. Conventional technologial regulations deal with imaginary "average" heat and "normal" conditions. For that reason and because of great value, each heat of stainless steel must be regarded as unique i.e., it must be processed in a specific way taking into account actual initial state and conditions (chemical composition, temperature, VOD ladle state, pumping system state, etc.). There is no such thing as standard process parameter. Every deviation of initial conditions from some imaginary standard can and must be compensated for by adequate adaptation of process parameters. Such a complex assignment can successfully be carried out only by computer aid.

The work was carried out as a part of the project Stainless Steel which is aimed at the reduction of production costs, improvement of the quality of stainless steel, development of new high quality and extra clean e.g. superferritic stainless steels and the optimization of EAF-VOD-CC tehnological line operation.

The research was concentrated to vacuum oxygen decarburization rate, which should be increased as much as possible since VOD treatment is serious bottleneck of the technological line particularly when producing ELI (Extra Low Interstitials) steel. In addition better control of melt temperature and lower carbon, nitrogen and phosphorus content especially in case of extra clean steel must also be considered in any optimization of VOD treatment.

2 Computer simulation and model tests

Main part of the research was carried out in the form of computer simulation of VOD treatment which is a key part of the technological line.

The model tests performed by use of CAPSS (Computer Aided Production of Stainless Steel) were undertaken

- to increase productivity by shortening of VOD treatment,
- to improve techno-economic production parameters and
- to determine most rational and expedient measures to be taken in order to improve the present technology

2.1 CAPSS

The PC oriented software CAPSS has been developed in Mathematical Modelling and Computer Simulation Department of IMT (Institute of Metals and Technologies) Ljubljana on the basis of a sophisticated mathematical model elaborated through extensive theoretical studies and investigations[1−10]. The model has been devised primarily for thermodynamical analysis of the Fe-Cr-C-Si-Mn-Al-Ti-O-N system in molten state which is essential in the production of stainless steel.

CAPSS integrates thermodynamic principles, industrial experience, theory of metallurgical processes and expert knowledge required for the economic and massive production of high quality austenitic, ferritic and superferritic conventional, ELC and ELI (Extra Low Carbon, Interstitials) stainless steel.

Thermodynamical data and published informations on VOD operation results were obtained from reference[11−33]. CAPSS was calibrated by a posteriori analysis of a number of heats which had been produced in steelworks Jesenice to determine some empirical unmeasurable constants typical for the steelworks. CAPSS was developed for:

- Off-line control of VOD (Vacuum Oxygen Decarburization) unit of EAF-VOD-CC technological line for the production of stainless steel
  - to reduce the operating costs
  - to increase the productivity and
  - to secure the high quality of produced steel
- Research and development purposes
  - to perform model tests by simulation of VOD operation in order to determine the effect of a change in process variables (oxygen blowing rate, oxygen and argon comsumption, lime addition, etc.) or initial conditions (e. g. melt composition, temperature, etc.) on operation results (productivity, production costs, quality of steel produced, etc.)
  - to optimize production technology and
  - to develop new grades of stainless steel
- Education and training purposes
  - for training of technical personnel in newly installed VOD units or steelworks and
  - for education of University students

2.2 *Computer control of VOD treatment*

Advantages of the computer control of VOD treatment are numerous and evident. Firstly, immediate and continuous inspection of the process of vacuum oxidation and development of melt temperature. It offers the possibility to stop oxygen blowing at exactly right time i.e., at desired final carbon content. The progress and rate of oxidation are continuously monitored and controlled in order

- to prevent melt temperature from exceeding allowable upper limit,
- to assure the lowest heat loading of ladle lining and
- to attain the maximum productivity and the lowest possible loss of chromium.

Computer control is beneficial also for reduction stage of VOD treatment since it

- offers monitoring of the reduction of chromium from slag and temperature changes,
- assures exact calculation of proper addition of lime and reducing means and
- helps to synchronize the operation of whole technological line EAF-VOD-CC and especially of VOD unit and consequent continuous casting machine.

For research and development purposes simulation of imaginary or real but future heats known also as model test is particularly useful. Similar model tests performed in the form of simulation of real past heats i.e., a posteriory analysis is very instructive in education and training of technical personnel. It can reveal errors and wrong decisions made in the past during VOD treatment of a given heat. Simulation and analysis of previous heats can be extensive and include all heats manufactured e.g. in the last month or year. Such an analysis is valuable for evaluation of the existent technology. It can help to find out and determine oscillations of techno-economic parameters (productivity, specific consumption of energy and raw materials, etc.) due to instable technology, unsuitable technical regulations, poor performance of technical personnel or inadequate maintenance. Particularly valuable is analysis of extreme heats i.e., exceedingly good and bad operation results. It can result in significant technological improvements and more suitable regulations. By all means it is first and obligatory step toward the introduction of computer control of steelmaking.

3 Optimisation of VOD treatment by computer simulation

3.1 *ELI stainless steel*

When producing ELI e.g., superferritic stainless steel denitrogenization of melt proceeds under deep vacuum (approx. 100 Pa) at a high carbon content. Of course, such a vacuum can be made only in especial and additional stage of vacuum treatment without oxygen blowing. There can be one, two or even more denitrogenization steps which depends on initial melt temperature and amount of heat losses. The extent and kinetics of this intermediary denitrogenization treatment can also be determined by model tests. Therefore, the efficiency of one stage and the necessity for multistage denitrogenization treatment to obtain required total (C+N) content can be established. As regards the oxygen blowing technique there are two methods namely, uniform and "smart" oxygen blowing. In final stage of oxidation decarburization rate is very small since the most part of oxygen is uitilized for harmful oxidation of chromium. Therefore, it should be smart and useful to decrease oxygen blowing rate gradually toward the end of decarburization.

Uniform oxygen blowing is another blowing technique which applies steady blowing rate e.g., 900 m^3/h and does not take into account rapid and continuous increase in the chromium/carbon activity ratio occuring in the final stage of decarburization. This change of thermodynamic conditions results in a drastically reduced decarburization rate and increased chromium oxidation rate which is accompanied with steep rise in melt temperature. Consequently, the final stage of decarburization is most delicate since VOD ladle lining must be prevented from thermal overloading. On the other side computer simulation in the form of model tests aimed at the optimization of VOD treatment should also optimize the productivity. The most appropriate compromise between high productivity and temperature limitation can be find out only by the use of computer simulation and model tests.

Model tests carried out by the use of CAPSS were planned to compare "smart" and uniform blowing (900 m^3/h) to find out the advantages and deficiencies of each.

The attention has ben focused at the productivity, extent of chromium oxidation to slag, maximum temperature at the end of oxidation and volume and kinetics of denitrogenization. Initial melt composition and temperature was 17.0% Cr, 1.20% C, 0.1% Si, 0.5% Mn, and 1550°C, respectively. Final carbon content should be lower or equal to 0.02 wt.% C. VOD treatment should be as short as possible to obtain high productivity of VOD unit however, melt temperature should not exceed 1700° degrees. The results of model tests are presented in figs. 1–4.

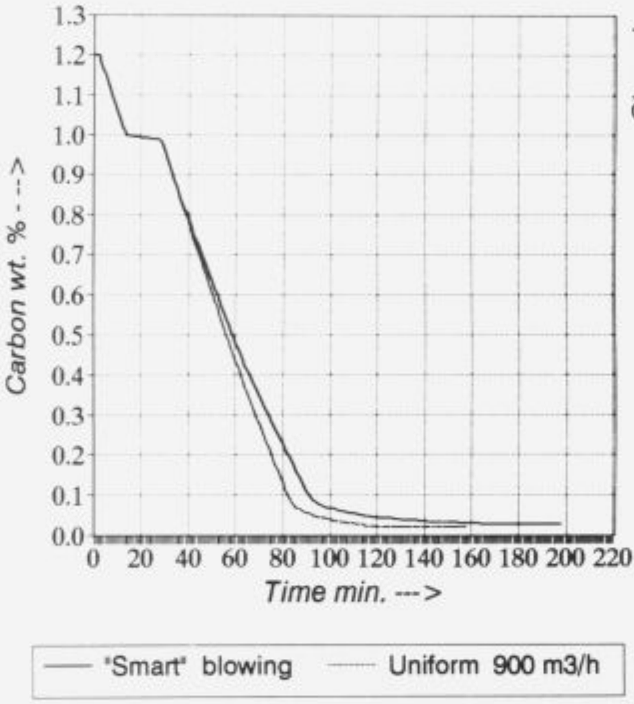

Figure 1. Influence of blowing technique on VOD productivity.
Slika 1. Vpliv načina pihanja na produktivnost VOD naprave.

As can be seen from **fig. 1** "smart" blowing characterized by continuously diminishing blowing rate toward the end of decarburization, as compared to uniform 900 m^3/h rate, results in a serious drop of productivity i.e., prolongation by 40 mins. of the time required for decarburization from 1.2% C to 0.02% C.

Quite unexpectedly, **fig. 2** shows that adaptation of blowing rate to the continuous change in thermodynamic conditions as applied by "smart" blowing does not reduce the extent of chromium oxidation to slag. There is no change in final chromium content which clearly does not depend on oxygen blowing method.

Uniform and intense oxidation with 900 m^3/h blowing rate results in the reduction of time required for VOD treatment by 40 mins. as can be seen from **fig. 3.** However, this increase in productivity could be too expensive since maximum melt temperature would exceed prescribed 1700°C limit.

Fig. 4 shows that blowing technique exerts practically no influence on the volume and kinetics of denitrogenization. Because of a higher melt temperature at uniform blowing favorable influence of temperature on denitrogenization of stainless steel can be seen.

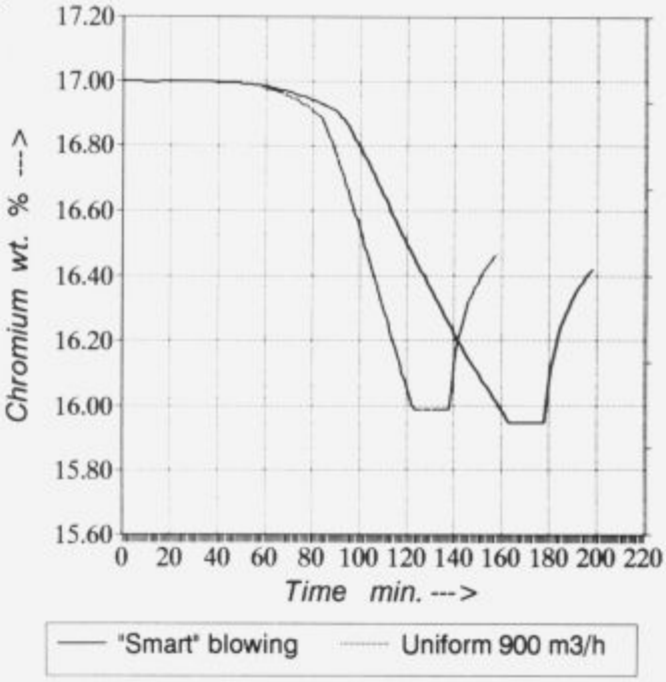

Figure 2. Effect of blowing method on the oxidation of chromium.
Slika 2. Vpliv načina pihanja na obseg in potek oksidacije kroma.

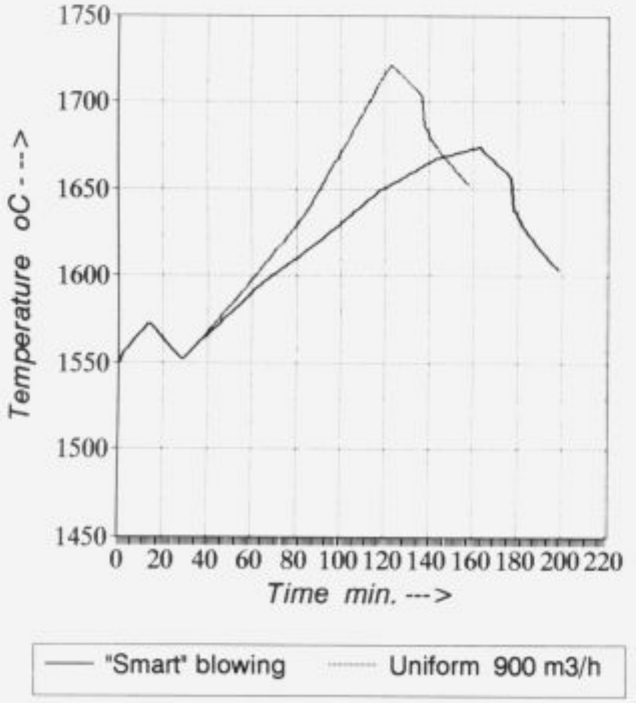

Figure 3. Effect of blowing method on melt temperature.
Slika 3. Vpliv načina pihanja na potek temperature taline.

3.2 Conventional stainless steel

The manufacture of ELI stainless steel e.g., superferritic steel differs from production technology for conventional stainless steel by intermediate stop of oxygen blowing followed by special usually 15 mins. long denitrogenization step at a high carbon content (approx. 1.0% C). Initial carbon content of melt planned for the manufacture of com-

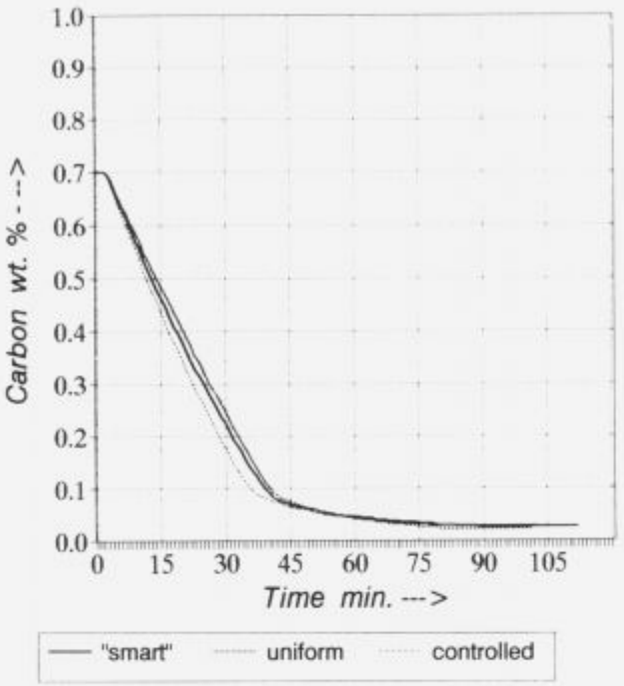

Figure 4. Influence of blowing technique on denitrogenization.
Slika 4. Vpliv načina pihanja na potek in hitrost razdušičenja.

mon stainless steel is therefore significantly lower in order to shorten VOD treatment. Final carbon conten of common steel is higher which also helps to reduce the time required for vacuum oxygen decarburization. Special denitrogenization stage is not necessary since low nitrogen content is not prescribed for common stainless steel. Except for ELC grades technological process for common stainles steel does not include final vacuum degassing stage followed by reduction. Therefore vacuum decarburization treatment can be performed also by controlled blowing rate in addition to "smart" and uniform blowing. The need for additional i.e., controlled oxygen blowing appears as a consequence of wider range wherefrom process parameters can be selected. The first aim of controlled blowing technique is to maximize the productivity of EAF-VOD-CC production line by shortening duration of VOD treatment which is the slowest stage and therefore VOD unit acts as a bottleneck. The problem is serious particularly in case of UHP electric furnace coupled with VOD unit. However, maximization of productivity by optimization of VOD must take into account following requirements:

- EAF tap temperature should be as low as possible,
- highest allowable temperature at the end of oxidation is 1700°C and
- melt temperature at the end of VOD treatment should correspond to the requirements of continuous casting (CC).

Exact solving of the problem is not possible. A compromise is needed between the contradictory requirements mentioned. Computer simulation i.e., a series of model tests carried out during tapping, ladle transport and preparation for VOD treatment is only possible. **Figs. 5, 6** and **7** present results of model test planned to determine most appropriate controlled blowing technique in order to optimize VOD treatment.

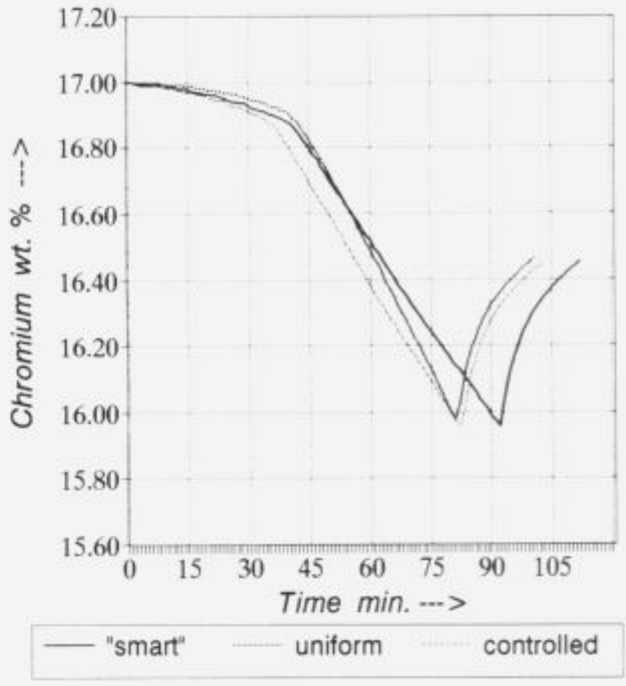

Figure 5. Optimization of VOD productivity by selection of proper blowing technique for common stainless steel.
Slika 5. Optimiranje produktivnosti z izbiro načina pihanja pri izdelavi klasičnega nerjavnega jekla.

As seen from **fig. 5** "smart" blowing requires longest time for decarburization. There is no essential difference in decarburization time at uniform and controlled blowing technique (101 mins. and 102 mins., respectively).

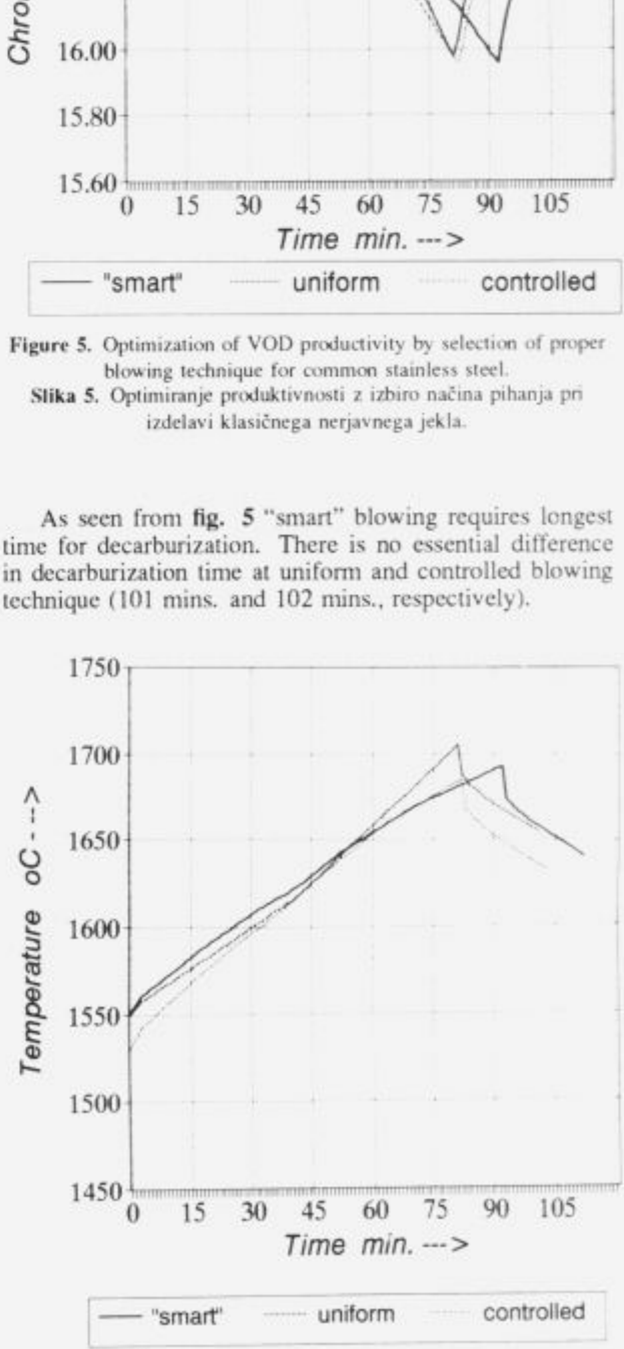

Figure 6. Influence of blowing method on chromium oxidation.
Slika 6. Vpliv načina pihanja na oksidacijo kroma v žlindro.

In all three cases chromium content at the end of treatment is the same as seen in **fig. 6.** This holds for both oxidation and reduction stage. However, it can be seen that during processing chromium content of melt is on the average lowest at controlled blowing because of lower initial temperature.

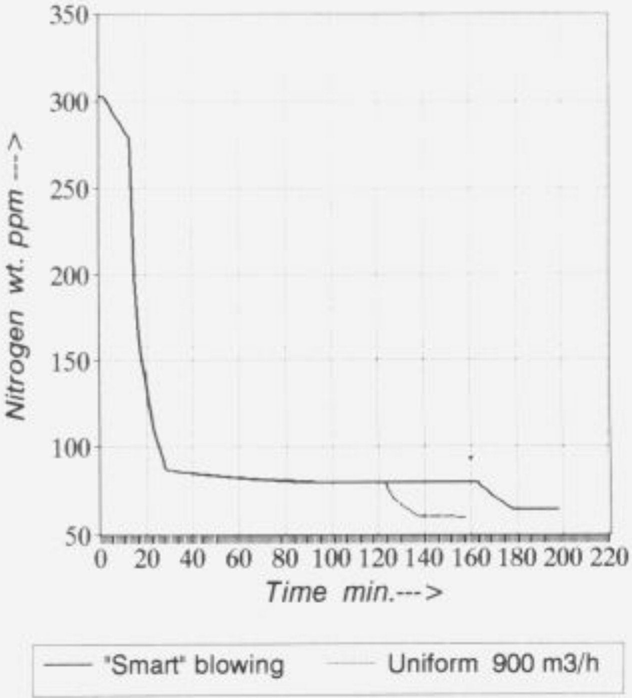

Figure 7. Influence of blowing method on thermal load of VOD ladle.
Slika 7. Vpliv načina pihanja na toplotno obremenitev VOD ponovce.

At uniform 900 m^3/h oxygen blowing rate (**fig. 7**) melt temperature at the end of oxidation just exceeded the allowable limit (1700°C). Heat load of VOD ladle is lowest at controlled blowing which is optimized to obtain practically the same productivity (102 vs. 101 mins.) at EAF tap temperature reduced by 20°C.

4 Conclusion

By the use of PC oriented software CAPSS which had been developed as a part of the research programme URP-C2-2566 computer simulation of stainless steelmaking EAF-VOD technology was carried out.

A series of model tests was performed to investigate the influence of three different oxygen blowing methods on the productivity of 90 ton VOD unit, chromium losses with slag, volume and kinetics of denitrogenization, and thermal load of VOD ladle.

Based on the results obtained following conclusions can be drawn.

- Common oxygen blowing technique known as "smart" blowing does not make it possible to reduce chromium losses. However, it has very negative influence on the productivity of VOD unit and consequently whole steelmaking EAF-VOD-CC technological line.
- Uniform oxygen blowing with constant blowing rate does not increase chromium losses to slag. By proper selection of blowing rate this blowing method can result in a higher productivity however, VOD ladle lining can be thermally overloaded.
- Best results can be achieved by computer controlled blowing rate which ensures highest possible productivity at lowest tap temperature and thermal load of VOD ladle.

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