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ANISOCHRONOUS MODEL OF THE METALURGICAL RH PROCESS

ANIZOCHRONNÍ MODEL METALURGICKÉHO RH PROCESU

Abstract

RH process is a metallurgical process, which serves for vacuum treatment of liquid steel by recirculation method, which *enhances quality of steel* that was made either in basic oxygen converter (BOF) or in electric arc furnace (EAF). The paper presents a project and verification of appropriate physically adequate *cybernetic anisochronous model* of this process. This model was obtained on the basis of measured and transformed data of dimensionless concentration of model liquid in the *physical model* of a pouring ladle with the RH chamber, constructed in the same length (geometric) scale 1:9 to the original objects. Mathematical model will be used for optimisation of RH process under operational conditions.

Abstrakt

RH proces je metalurgický pochod, který slouží k vakuování tekuté oceli recirkulačním způsobem za účelem *zvyšování kvality oceli* vyrobené v kyslíkovém konvertoru anebo v elektrické obloukové peci. V příspěvku je prezentován návrh a ověření vhodného fyzikálně adekvátního *kybernetického anizochronního modelu* tohoto procesu. Uvedený model byl získán na základě naměřených a transformovaných údajů bezrozměrové koncentrace modelové kapaliny ve *fyzikálním modelu* licí pánve s RH komorou, sestrojených ve stejném délkovém (geometrickém) měřítku 1:9 k dílu. Matematický model bude použit k optimalizaci RH procesu v provozních podmínkách.

1 INTRODUCTION

During the period 2006/2007, in the *Laboratory of physical and numerical modelling of metallurgical processes* at the Department of metallurgy (DM) of the Faculty of Metallurgy and Materials Engineering of the VŠB-Technical University of Ostrava, were manufactured *physical models* of PL and RH chamber in the same length (geometric) scale 1:9 to the original objects. The first series of experiments was realised on these models in May 2007.

2 DESCRIPTION OF MODELS AND PROCESSES

Schematic representation of situation at vacuum treatment of steel (in water model) by an inert gas (argon) in the model of the pouring ladle (*mPL*) with use of the model of the RH chamber (*mRH*) is shown in Fig. 1.

Brief technological description of the process is the following: negative pressure (*V*) "lifts up" the level of the model liquid (coloured water enriched in concentration) and pushes it into the RH chamber. After stabilisation argon (bubbles) with constant volume flow q_1 is brought into the bottom part of the inlet tube (marked *A* - left) primarily from special nozzles (*Tr*), located along the perimeter

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of the tube.

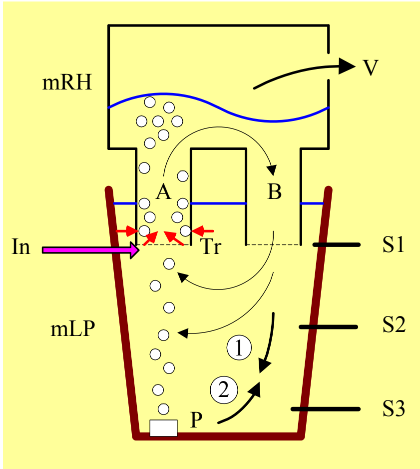

Fig. 1 Blowing of argon into the pouring ladle model with the RH chamber

It is possible to bring argon (with constant volume flow q_2) secondarily also from eccentrically situated blowing element *P* (blowing brick) at the bottom of the *mPL*. Tracing element (time 0) is injected at the tube inlet (*In*) at model experiments. Due to flowing of liquid through the chamber the tracing substance passes with the liquid through the inlet tube (*A*) and leaves the chamber through the outlet tube (marked *B* - right) into the ladle (*mPL*). The electrical conductivity sensors S1, S2, S3 register concentration changes in the bath during the vacuum treatment.

After the liquid passes through the chamber it is "pumped" again by the inlet tube (*A*) and after it has passed the RH chamber the sensors indicate already lower *concentrations*. This cyclic progressively *homogenises* the contents of the pouring ladle till stabilisation at the final concentration of the bath. Two pressure forces are in fact exerted on molecules of the liquid near the sensors *S2 (situated lower)*, and mainly *S3*: ***1*** (*recirculation*, cyclic) and ***2*** (*resistant*).

3 MEASURED DATA

Analysis and synthesis of mathematic model was realised on the basis of the results from the first series of experiments. Time behaviour of the measured concentration *c3(t)* at the sensor *S3* in experiment *Test8* was chosen for documentation and representation – see Fig. 2:

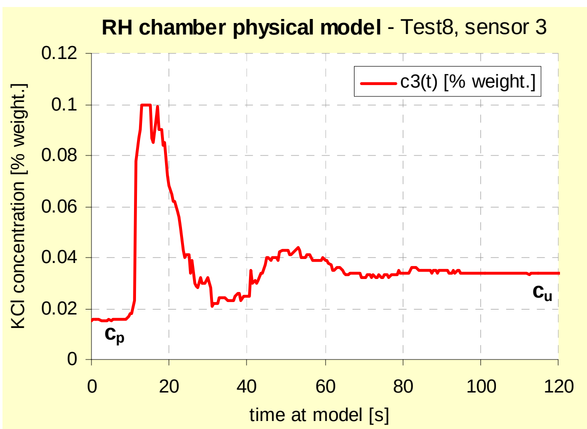

Fig. 2 Time behaviour of the measured concentration at the lower sensor *S3*

The time behaviour of concentrations at sensors shows several obvious general facts. Start and time behaviour of bubbling of gas through steel can be reflected by approximation in the form of *Heaviside unit step* and it is therefore possible to understand time behaviour of concentration as *unit step response*. At the initial phase of the first overshoot of unit step response certain *time delay* is obvious, which is given by the time from the injection of tracing substance till its registration by the sensor. This fact is not so directly and outwardly obvious at following cycles (overshoots). Although the existing time delay is still taking effect but it is hidden latent "internal".

4 FIRST IDENTIFICATION OF THE PLANT

It is possible to assess on the basis of theoretical knowledge and experience that transient performance of investigated system reminds ***oscillating*** (so called inherent) ***proportional plant with inertia of the 2^nd^ order*** (*Sp2k*). This plant could be *physically adequate* for investigated process since it is possible to define for the liquid both hydraulic *capacity* and hydraulic *inductivity* [NOSKIEVIČ 1999]. Verification of this hypothesis is possible by deterministic identification with use of unit step response. The relevant literature – e.g. [NOSKIEVIČ 1999], [VÍTEČKOVÁ 1998] and [FIKAR & MIKLEŠ 2003] states however that evaluation of unit step responses of oscillating proportional regulated plants is *very demanding*. The above cited literature references give *three* different simple approaches to identification. But results of the mentioned identification methods indicate *unsuitability* and *inapplicability* of this model (due to the fact that it is impossible to achieve with it the necessary *damping* and at the same time corresponding *periods* of the unit step response).

5 SECOND IDENTIFICATION OF THE PLANT

Failure of the first falsely „heuristic" identification points to the necessity of use of mote complicated mathematical model.

5.1 Approaches to solution

Exact ***physical-mathematical*** (theoretical) ***description*** of processes running at vacuum treatment of steel with use of argon would be very complicated and it would lead to the system of *non-linear partial differential equations* describing transfer of *momentum*, *heat*, *components* with exciting function in the form of an equation of so called *deterministic chaos* (argon bubbling). This approach was for the RH process in certain extent already described in the literature.

Another suitable solution consists in use of so-called ***compartments*** [ZÍTEK 1990]. Compartment is a fictitious element formed by *concentration* and *separation* of the object properties in certain zones of the space. In the analysed case of behaviour of processes in the model of PL with RH chamber it is possible to arrive after intuitive spatial discretisation of continuum (bath) to *two compartments* acting against each other and marked „pressure powers" ***1*** and ***2*** (Fig. 1).

5.2 Anisochronous proportional plant of the 1st order

We will use hereinafter a simple basic ***anisochronous proportional plant*** (model) ***with inertia of the 1st order*** (with time delay at the *input* and also at the *feedback*, *Sap1*) with Laplace (L) transfer:

$$G(s) = \frac{k_1 \cdot e^{-T_{du}s}}{T_1 s + e^{-T_{dy}s}} = \frac{k_1 \cdot \exp(-T_{du}s)}{T_1 s + \exp(-T_{dy}s)} = \frac{Y(s)}{U(s)} = \frac{M(s)}{N(s)}, \tag{1}$$

where: k_1 – static sensitivity coefficient (≈ transfer) of the model (plant), T_1 – transition time constant ≈ time constant of the plant [s], T_{du} – time delay of the input value of the plant [s], T_{dy} – time delay of the output value in a feedback [s], $Y(s)$ – L-image of the output which is the measured concentration, $U(s)$ – L-image of the input which is the argon flow rate, $M(s)$ – numerator of a transfer function (zeroes of transfer), $N(s)$ – denominator of a transfer function (poles of transfer).

Characteristic equation (which is transcendent in the form of the so called *quasi-polynomial* and allows therefore unlimited number of solutions in the complex range – see [ZÍTEK & VÍTEČEK 1999]) is the following for this plant:

$$N(s) = T_1 s + e^{-T_{dy} s} = T_1 s + \exp(-T_{dy} s) = 0\,. \tag{2}$$

Its solution in the complex range is possible with use of special function of complex variable, so called ***Lambert W – function***, see [WEISSTEIN 2005], from which we get after more transparent and simple notation $T_{dy} = T_d$, the following:

$$\boxed{s(T_d, T_1) = \frac{W\left(-\dfrac{T_d}{T_1}\right)}{T_d}}\,. \tag{3}$$

It is possible to choose for more illustrative view in a 2D plane for example T_1 = 10 s and to show (see Fig. 3) dependence of *real* and *imaginary* part of solution (3) of the above mentioned characteristic equation (2) on the parameter of time delay $T_d \in (0, 20)$ s:

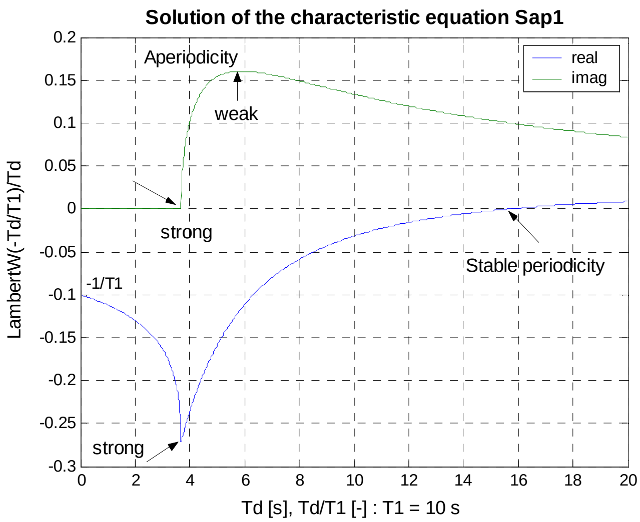

Fig. 3 Real and imaginary part of the solution of characteristic equation *Sap1*

Fig. 4 shows graphic presentation of marginal values (important points) of changes of character of unit step response:

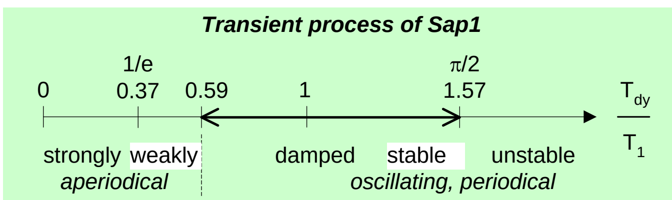

Fig. 4 Marginal values of transient process of the model *Sap1*

5.3 Differential compartment model

On the basis of the scheme *mPL* and *mRH*, as well as time behaviours of concentration, a simplified so-called minimum model was proposed. This model is based on counterwork of *compartments* („pressure powers“) ***1*** and ***2*** (see Fig. 1) and in past this principle was successfully used for the model of the pouring model itself *mPL* [MORÁVKA, MICHALEK & KOHOUT 2006].

The described process was interpreted as *cybernetic* model, which can be illustratively demonstrated by the *block diagram* – see Fig. 5:

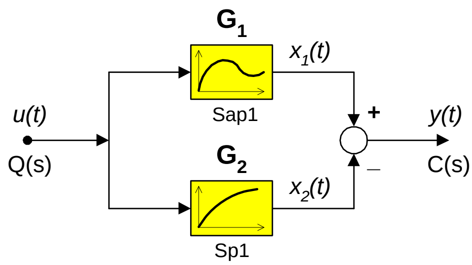

Fig. 5 Block diagram of *mRH*

The model is valid for any sensor *S1*, *S2*, *S3*, notation *Q(s)* means L-image of argon flow, *C(s)* is L-image of concentration. It is therefore connection of two parallel and counter-acting *proportional* elements, namely one *anisochronous* and the second classical *isochronous*.

Generalised *functional* or *anisochronous state formulation* of the proposed model of the RH process has the following form:

$$\left\{ \begin{aligned} &\frac{dx_1(t)}{dt} = \frac{k_1}{T_1}\cdot u(t) - \frac{1}{T_1}\cdot x_1(t - T_{d1}) \\ &\frac{dx_2(t)}{dt} = \frac{k_2}{T_2}\cdot u(t) - \frac{1}{T_2}\cdot x_2(t) = \frac{k_1 - 1}{T_2}\cdot u(t) - \frac{1}{T_2}\cdot x_2(t) \\ &y(t) = x_1(t) - x_2(t) \end{aligned} \right\}. \qquad (4)$$

5.4 Modelling and simulation identification of the model

The differential compartment anisochronous model *mPL* with *mRH* was in *graphical* form modelled in the environment of the program *Simulink* (see Fig. 5). However, modelling and simulation parametric identification was much simpler in the environment of the simulation program *20-sim 2.3 Pro Shareware* [ZÍTEK & PETROVÁ 1996], simply by entering the *textual* form of the system of equation (4). Fig. 6 shows the graphical output of result of simulation identification in the program *20sim*:

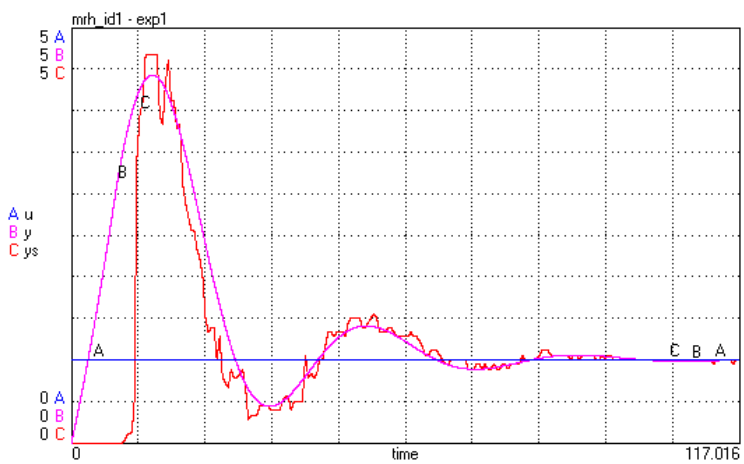

Fig. 6 Measured and approximated time behaviour of the unit step response *mRH*

It is obvious from the Fig. 6 that simulation parametric identification offers *acceptable* and *usable* results. The following values were obtained for normalized values of concentration from the sensor *S3* at the experiment *Test8*: $k_1 = 5.2$, $T_1 = 8.2$ s, $T_2 = 12.8$ s, $T_d = 7.5$ s.

5 CONCLUSIONS

The paper describes *compartment* physically adequate approach to searching of suitable cybernetic-mathematical model of behaviour of equipment of the *pouring ladle with RH chamber* with use of signal of measured and normalized concentration of tracing substance in reduced *physical model*. Dampened oscillating time behaviour of gas (argon) blowing was modelled by combined (differential) *compartment* model, containing *anisochronous* proportional plant of the 1^{st} order.

Results of analyses will be further developed and used for *optimisation of the operating* mode of gas blowing (determination of its optimum flow) on the given equipment at the Třinec metallurgical plant (TŽ), a.s. for determination of the so called *circulation* mass (or volumetric) *flow* of liquid (steel) through the chamber, which cannot be measured directly (not even in modelling conditions, mainly due to argon supply), also for *teaching* at the Technical University of Mining and Metallurgy in Ostrava (VŠB-TUO).

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