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GAS MALDISTRIBUTION IN A FERMENTER STIRRED WITH MULTIPLE TURBINES

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Abstract. The study is focused on modelling of gas maldistribution of aerated liquid systems in a multiple impeller bioreactor. The phenomenon may or may not depend on column design. The latter case is dependent merely on bed fluid dynamics and could be treated by using the methodology of the residence time distribution (RTD) theory. Accordingly, a specific methodology is proposed, as follows: the fermenter has been modelled as a reactor network involving a combination of zones representing basic ideal flow patterns. The methodology is based on the wide-spread experimental gas tracer technique extended by a new systemic identification approach. The approach is based on a Mellin-modification of the Laplace transform over the relevant equations. The method allows zero-time solutions for identification analysis. Unlike the diffusion model approximation, the technique considered allows exact approximation of the RTD curves with circulation. The proposed transfer function represents adequately the bioreactor gas maldistribution thus allowing fast overview of the studied reaction and prompt feed back control on the physical situation.

Key words: RTD, Transfer function, identification, triple impellers;

1. INTRODUCTION

The liquid phase in large scale industrial bioreactors is usually backmixed and its modeling does not account for the influence of gas phase backmixing and maldistribution. Consequently, production yield and biomass growth may be overestimated or underestimated. Information on the gas flow behavior is also important for mass transfer and reaction control, in gas-liquid reactors modeling, as well in rational design of this type of equipments. Recently, the amount of studied in the case of multi-impellers systems carried out in this area in created [1-10].

Initially, attention has been focused on single impeller tanks. Nienow et al. (1978)[11] (see also Middileton and Smith (2004) [12] demonstrated the effect of gas flow patterns by gradually increasing the gas throughout or decreasing the impeller speed. These workers determine the critical speed for complete dispersion. At low gas flow rate and high impeller speed, the bubbles appeared well dispersed both above and below the impeller. While increasing the gas flow rate, the gas dispersion become incomplete, and by further increase lead to “flooding”. Under flooded condition, not all the gas flows through the gas cavities and part of it is not dispersed by the impeller. At this state, the impellers virtually stop pumping in the radial direction and bulk liquid circulation is set up by the rising bubbles [12].

Recent developments in dual-axial and mixed impeller design have shown that the gas- liquid reactor behavior is rather complicated [7]. The multiple impeller aerated bioreactors importance rose due to their high efficiency of gas utilization. In general, the formation of gas flow patterns is a function of volumetric gas flow rate and rotational speed. Clearly, “flooding” is an undesirable condition that should be avoided since liquid phase mixing, gas dispersion and gas liquid mass transfer are adversely affected. The phenomenon may or may not depend on column design. Referring to the latter case, it could be treated by the residence time distribution (RTD) methodology.

This study is focused on modeling of gas maldistribution of aerated liquid systems in a multiple impeller bioreactor. It is well known [1] that two opposite strategies are available: the use of powerful and complex CFD simulation and the development of phenomenological semi-empirical models. In the latter case, the gas has been assumed to behave ideally or non-ideally and has been modeled by simple models. The case appears [6] to be of great interest when the predictive method based on CFD codes cannot be used. In particular this happens while modeling gas phase behavior in gas-liquid contactors in presence of complex phenomena effects, such as bubbles break-up and coalescence description, prediction of bubble size distribution, calculation of bubble generation rate.

Gas dynamic behavior is a statistical phenomenon and a distribution coefficient may be used to characterize the divergence between plug flow with axial dispersion (PFD) and ideal plug flow (PF). The use of these models in stirred tanks with multiple impellers is critical due to bad fitting of the experimental RTD curves originating from the dynamic technique. [9,13]

On the after hand, the small bubbles in viscous systems are usually backmixed by the liquid phase and their behavior differs from the one of the large bubbles and could be considered as perfect mixing. In presence of two types of bubbles, the evaluation of gas-liquid mass transfer by using the conventional technique becomes inaccurate and the PFD model stands unrealistic [14]. Pinelli (2005) [1] proposed a new two gas fraction model (TGF model) intended to overcome some of the limitations evidenced by the classical PFD model. In the two fractions model (TGF) the large bubbles are treated by a PFD model, and the small bubbles are considered as completely mixed. In particular, this model has been proposed to interpret the gas phase behavior and mass transfer in viscous and non-coalescent solutions with significant presence of small (less to 1mm) bubbles.

As mass transfer take place, the liquid mass transfer coefficient (k_L) is assumed to be similar for both large and small bubbles. However, the greater volumetric interfacial surface of the small bubbles exhibits high k_La values. Provided that mass transfer is controlled by one of the two phases, the choice of a suitable model to describe the fluid dynamic behavior of both the liquid and the gas phase can be simplified. The effect of gas – side axial mixing in case of liquid-side controlled mass transfer processes is usually small and a more simple gas flow model (i.e. Plug Flow) could be formulated. In all other cases, this is not sure or practically impossible.

The present study is focused on RTD modeling of gas maldistribution of aerated systems in a multiple impeller reactor. The methodology proposed is based on the step change disturbance technique extended by a new systems identification approach.

2. EXPERIMENTAL METHODS

The experiments were carried out in a semi-technical scale stirred vessel with tank diameter T= 0.4 m and aspect ratio H/T = 2 [5], where H is liquid height. The tank was agitated by three or two Rushton turbines. A standard geometry T/3 was configured for comparison with similar data regarding a single Rushton turbine and a fluid-foil impeller NS described by Vlaev et al. (2005) [15]. The tank had a dish bottom. The off bottom impeller clearance was T/6. Gas was fed through a ring sparger (d_s/d =0.75) at 3 cm below the bottom impeller.

The gas flow behaviour was studied in a non-coalescing system representing a specific medium for cultivation of *Bacillus subtilis ATCC 21332* containing 4% glucose solution and mineral salts. Demineralised water was used as a reference coalescing system. The experiments were carried out in semi-batch conditions at room temperature and atmospheric pressure. The operating conditions were N=1-4s^{-1} and Q_g = 500-3000 dm^3/h.

The RTD curves were obtained following step change disturbances in the gas feed (nitrogen into air). Oxygen concentration was analyzed continuously by SERVOMEX 4100 analyzer equipped with a paramagnetic detector. All the experiments at each rotational speed were duplicated for checking their reproducibility. The model was formulated as a network of discrete ideal flow components: plug flow (PF) and perfect mixing (PM) combined. Each component was characterized by specific parameters (volume and flow rate). The model adjustment was carried out by comparison between the simulated model response to a stimulus, and the experiments response.

3. RESULTS AND DISCUSSION

The study objective has been to formulate a method (a new technique) for evaluation (characterization) of gas-phase RTD (residence time distribution) in aerated stirred vessels. The new systemic identification approach was based on a Mellin modification of the Laplace transform over the relevant equations [16].
In order to determine the gas-phase RTD in aerated stirred reactors based on response curves to feed step change disturbances, a mathematical model describing the concentration time-course of such system, was proposed. The model included the transfer function.

$$H(p) = \frac{C_{out}(p)}{C_{in}(p)} = \sum_{i=1}^{N} \frac{k_{i} \cdot e^{-Ti.p}}{(p+a_i)^{ni}} \qquad (1)$$

The following flow chart represented the model network (Fig. 1):

In order to determine the number of the series that represent the network, the second derivative of the response curve was determined numerically. Thus, the slope changes corresponding to the separate effects (phenomena) could be evaluated. Correspondingly, the slope changes represented the series of the relevant model network. Prior to the analysis, the output was filtered and the high frequency noise was eliminated. A second order Butterworth filter with 15 Hz breaking frequency positioned downstream of the spectral analysis output device was used in the operation [17].

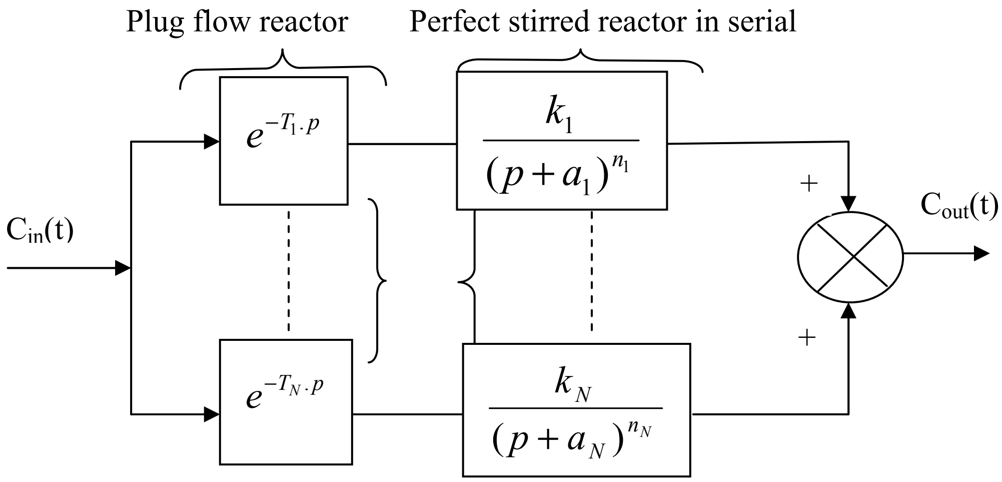

Fig. 1 Model network Representation

The other reactor network parameters were determined based on the convolution principle applied to the reactor output concentration $C_{out}(t)$:

$$c_{out(t)} = \int_0^t c_{in}(t-u).h(u).du \tag{2}$$

where *h*(u) indicates the inverse Laplace transform function of the model, H(p), characterized by

$$h(u) = \sum_{i=1}^{N} k_i \frac{e^{-a_i(t-Ti)}.(t-T_i)^{n_i-1}}{\Gamma(n)} \tag{3}$$

Γ in equation (3) represents the gamma function.

Parameters H(p) corresponding to the separate network branches can be determined by optimization using the least squares criterion applied to the difference between the output $C_{out}(t)$ and the experimental data. Regarding the operation *regimes* subject to *validation*, the following constraints have to be considered:

$$\sum k_i = Q_g \tag{4}$$

$$\sum T_i \frac{k_i}{a_i^{n_i}} Q_g + \sum n_i \left[\frac{k_i}{a_i^{n_i}} \frac{Q_g}{a_i} \right] \le V_{reactor} \tag{5}$$

$$J = \min \int_0^t \left(c_{\exp}(u) - c_{out}(u)\right)^2 du \tag{6}$$

A typical exemple of the response curves to step change disturbances in the gas feed is shown in Fig.2. Typically, the response curves are different depending on the gas flow rate at constant rotational speed. The curve comparison (experimental to theoretical) is shown in Fig.3.

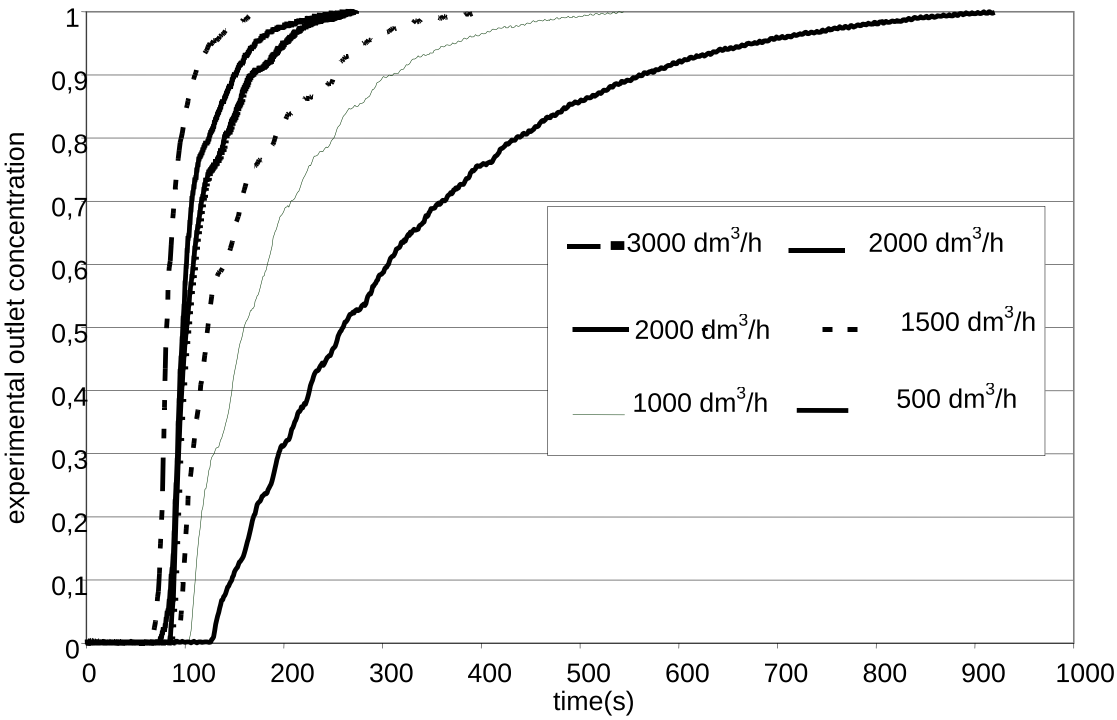

Fig. 2 Typical response curves taken at different flow rates: fermentation medium, $N=1s^{-1}$, 3 impellers

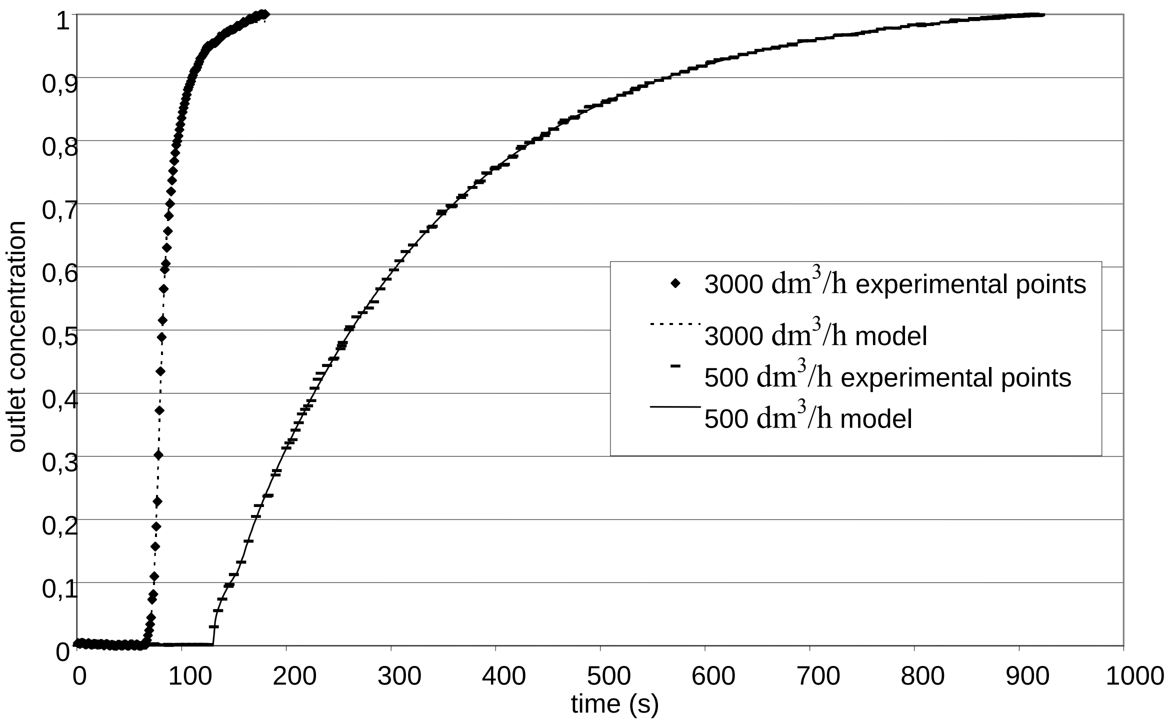

Fig. 3 Exemple of fiting of experimental and theotitical curves at different flow rates : *fermentation medium, $N=1s^{-1}$, 3 impellers*

It is worth noting, that the shape of the experimental RTD curves obtained with specific medium for cultivation of *Bacillus subtilis ATCC 21332* containing 4% glucose solution and mineral salts (a non-coalescing system) was reproduced very well and rapid (Table 1and 2) with the proposed model (combination of elementary ideal flow systems: plug flow (PF) and perfect mixing (PM). The same result is obtained with water.

T_i(s)	a_i(1/s)	n_i	k_i
6,38E+01	3,40E-03	1,30E+01	7,86E+29
1,13E+02	3,06E-02	1,81E+01	3,62E+25
1,31E+02	9,43E-03	6,08E-01	3,95E+00
1,59E+02	5,51E-03	1,19E+00	3,44E+02
1,53E+02	1,40E-01	1,16E+00	2,99E-01

Table 1**:** Values of model parameters at Q_g = 500 dm^3/h.

T_i(s)	a_i(1/s)	n_i	k_i
4,47E+01	1,29E-01	6,82E+00	4,56E+05
5,82E+01	8,19E-01	1,75E+01	1,93E+01
5,66E+01	3,60E-03	1,08E+01	2,78E+24

Table 2: Values of model parameters at Q_g =3000 dm^3/h

The model correctly predicts the evolution in vessel behavior with increasing of gas flow rate (Fig.4, low constant rotational speed: N=1s^{-1}). At the lowest gas rate, the volume of reactor dead zones is important. With increasing gas rate, the plug flow reactor behavior is observed and at higher gas rates the plug flow model seems, therefore, to be acceptable for describing the behavior of the gas phase in this equipment, especially at low rotational speed.

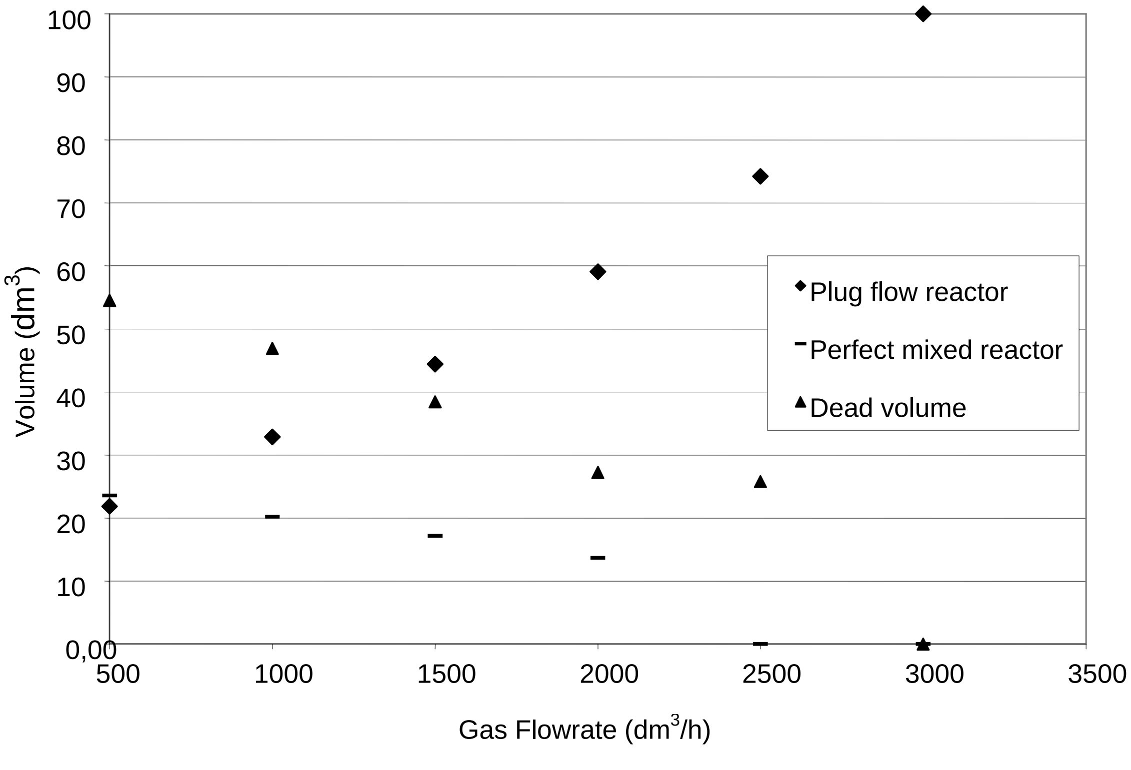

Fig. 4 Information on the gas flow reactor behavior at different flow rates for N=1s^{-1}

4 CONCLUSIONS

The study is focused on modelling of gas maldistribution of aerated liquid systems in a multiple impeller bioreactor. Accordingly, a specific methodology is proposed, as follows: the fermenter has been modelled as a reactor network involving a combination of zones representing basic ideal flow patterns (perfect mixed flow (PMF) and plug flow (PF)). The approach is based on a Mellin-modification of the Laplace transform over the relevant equations. The method allows zero-time solutions for identification analysis. Unlike the diffusion model approximation, the technique considered allows exact approximation of the RTD curves with circulation. The function transfer proposed represents adequately the bioreactor gas maldistribution thus allowing fast overview of the studied reaction and prompt feed back control on the physical situation.

Nomenclature:
k_i: static gain
T_i: delay time (s)
a_i: pole (s^{-1})
n_i: system order
N: series number
C_{out}: output concentration
C_{in}: input concentration
C_{exp}: experimental output concentration
Q_g: gas flowrate ($dm^3.h^{-1}$)
$V_{reactor}$: reactor volume (dm^3)
p: Laplace variable

References:

1. Pinelli D., 2005. "A phenomenological model for the gas phase flow in high-aspect-ratio stirred vessels: the role of small bubbles in non-coalescent and moderately viscous liquids", *Chemical Engineering Science*, **60**, 2239-2522.
2. Majirova H., Pinelli D., Machon V., Magelli F., 2004. "Gas flow behaviour in a two-phase reactor stirred with triple turbines", *Chem. Eng. Technol.*, **27**, 304-309.
3. Gogate, P.R., Beenackers A.A.C.M., Pandit A.B., 2000. "Multiple-impellers systems with a special emphasis on bioreactors: a critical review", *Biochemical Engineering Journal*, **6**, 109-144.
4. Hristov, H.V., Mann R., Lossev V., Vlaev S.D., 2004. "A simplified CFD for three-dimensional analysis of fluid mixing, mass transfer and bioreaction in a fermenter equipped with triple novel geometry impellers", *Food and Bioproducts Processing*, **82**, 21-34.
5. Djebbar R., Roustan M., Line A., 1996. "Numerical computation of turbulent gas-liquid dispersion in mechanically agitated vessels", *Chemical Engineering Research and Design*, **74**, 492-498.
6. Ranade V.V., Perrard M., Xuereb C., Le Sauze N., Bertrand J., 2001. "Influence of gas flow rate on structure of trailing vortices of Rhuston turbines: PIV measurements and CFD simulations", *Chemical Engineering Research and Design*, **79**, 957-964.

7. Bouaifi M., Roustan M., 2001. “Power consumption, mixing time and homogenisation energy in dual-impeller agitated gas-liquid reactors”, *Chemical Engineering and Processing,* **40**, 87-95.
8. Vasconcelos, J.M.T., Orvalho, S.C.P., Rodrigues, A.M.A.F., Alves, S.S., 2000. “Effect of blade shape on the performance of six-bladed disk turbine impellers”, *Industrial and Engineering Chemistry Research*, **39**, 203-213.
9. Pinelli, D., Magelli, F., 2000. “Analysis of the fluid dynamic behavior of the liquid and gas phases in reactors stirred with multiple hydrofoil impellers”, *Industrial and Engineering Chemistry Research,* **39**, 3202-3211.
10. Dee N.G., Solberg T., Hjertager B.H., 2003. “Flow generated by an aerated Ruhston impeller: two-phase PIV experiments and numerical simulations”, Canadian Journal of *Chemical Engineering*, **80**, 638-652.
11. Nienow A.W., Wisdom D.J., Middleton J.C., 1978. “The effect of scale and geometry on flooding, recirculation and power in gassing”, *Proc. 2nd Eur. Conf. on Mixing*, BHRA, Cranfield, pp. F1-F16.
12. Middileton, J.C. , Smith, J.M., 2004. *Gas-liquid mixing in turbulent systems*, Handbook of Industrial Mixing. Wiley. New Jersey.
13. Nocentini M., Magelli F., Pasquali G., 1988. “On the modeling of the gas behavior of gas-liquid vessels stirred with multiple impellers”, *Proc. 6th Eur. Conf. on Mixing* (Pavia, 24-26 May), BHRA, Cranfield, pp. 337-344.
14. Linek V., Moucha T., Sinkule J., 1996. “Gas-liquid mass transfer in vessels stirred with multiple impellers I. Gas-liquid mass transfer characteristics in individual stages”, *Chemical Engineering Science*, **51**, 3230-3212.
15. Vlaev S.D., Nikov I., Martinov M. “Velocity gradients in impellers-agitated power law fluids at transitional mixing”, Proc. *ISMIP*", (Sevilla, 1-4 June).
16. Dubois D., Brienne J.P., Povy L., Baussart H., 1996, “Study of a system described by an implicit derivative transmittance of non integer with or without time delay”, Proc. *IMACS-IEEE "CESA'96*", (Lille, 9-12 July), pp. 85-90.
17. Parks T.W., Buris C.S, 1987. *Digital Filter Design*. John Wiley & Son, New York.