

# Experimental studies of two-phase liquid metal-gas chain flow with ultrasonic echo pulse method and in the magnetic field of permanent magnets

Artur Andruszkiewicz<sup>1,\*</sup>, and Kerstin Eckert<sup>2</sup>

<sup>1</sup> Wrocław University of Science and Technology, Wybrzeże Stanisława Wyspiańskiego 27, 50-370 Wrocław, Poland

<sup>2</sup> Technische Universität Dresden, Faculty of Mechanical Science and Engineering, George-Bähr-Strasse 3c, 01069 Germany

**Abstract.** Metallurgical processes of refining and degassing liquid metals are related to the blowing-in neutral gasses like for example argon. Effectiveness of the process depends on the flowing gas parameters like: dimensions, velocity, distribution and gas phase flow zone. These parameters can be changed under the influence of outside magnetic field and formed by it a Lorentz' force. In order to get full information of rising bubbles essential are certain measuring methods. Among many of these the ultrasonic echo pulse method is likely to be the most intensive developed in the past few years. That method enables estimation of gas phase flow parameters in a range from individual bubble flow up to full continuous gas flow at the inlet nozzle. In this paper a measurement principle has been described for an ultrasonic echo method and there also submitted and discussed results of obtained results for diphas flow of GaInSn-argon.

## 1 Introduction

The two-phase liquid metal-gas flow appears in many technological processes like in metallurgical process of after-furnace steel refining. The process of liquid metal degassing, purification or enrichment are directly related to argon blow-in. A refining efficiency depends on the dimension of rising bubbles, its contact time with metal, the rise zone, and the flow stream of bubbles. A proper recognition of these parameters enables optimization as well as control of metallurgical processes. In order to get a complete knowledge of the rising gas bubbles an experimental studies of two-phase liquid metal-gas flow are essential. Among many methods of investigation two-phase flows recently more and more important becomes the ultrasonic method. For example, the ultrasonic echo pulse method is presently used by TU Dresden for identification of two-phase liquid metal-gas flow parameters in their project studies on "Elektromagnetische Stromungsbeeinflussung in Matallurie, Kristallzuchtung und Elektrochemie" no SFB 609.

The aim of the article is to present selected research results: rise velocity of bubbles, its creation frequency, dimensions and flow zone in the liquid metal using the echo pulse method. The method has been elaborated for a container filled with liquid metal Ga<sup>68</sup> In<sup>20</sup> Sn<sup>12</sup> where the argon gas phase was blow-in through a nozzle. Measurements were also done in magnetic field of permanent magnets having magnetic induction of  $B=300$  mT. Magnetic field influences the rise velocity and the final velocity of gas bubbles, the movement trajectory

and the zone of gas phase flow as well as the drag coefficient value. The article also compare the gas phase flow parameters in the liquid metal in motion, in the magnetic field and without the magnetic field.

## 2 Ultrasonic echo pulse method – the measurement principle

Among many methods of two-phase liquid metal-gas flow studies the biggest significance have got the non invasive techniques. Its basic advantages are no interference with the flow, no perturbations of velocity profile distribution and no changes of position distribution and diameter of rising bubbles. A non invasive techniques enable assign the basic two-phase flow parameters practically in a real time. In the studies are used ultrasonic Doppler's methods (UDV) [1-3], tomography techniques: positron-emission PET and roentgen CT [4] as well as methods utilizing eddy current and magnetic sensors [5-6]. The ultrasonic echo pulse method which can be used in identification of two-phase liquid metal-gas flows it is not yet fully developed and propagated comparing to the other above mentioned methods. That method is most widely used in non invasive material investigation - ultrasonic defectoscopy. It is a primary way of material fault detection also giving the localization, dimensions and space orientation of the defects. Presuming a gas phase as flow discontinuity than the echo pulse method can be utilized to estimate characteristic parameters of two-phase liquid metal-gas flow.

The primary work pertaining to estimation of liquid metal-gas flow parameters with utilized echo method

\* Corresponding author: [artur.andruszkiewicz@pwr.edu.pl](mailto:artur.andruszkiewicz@pwr.edu.pl)



such a way that the amplitude of signals over passed 20% of the level shown on Fig.1. The signal sampling period equals 0.7 ms. The recording period was set at 360 s, according to a principle proved by Sommerlatt [7] that to get representative results a sampling period have to be longer than 2minutes. For such recording time it is possible to record even several thousand rising bubbles and exactly estimate its rise velocity and rise zone, depending on the creation frequency of argon bubbles.

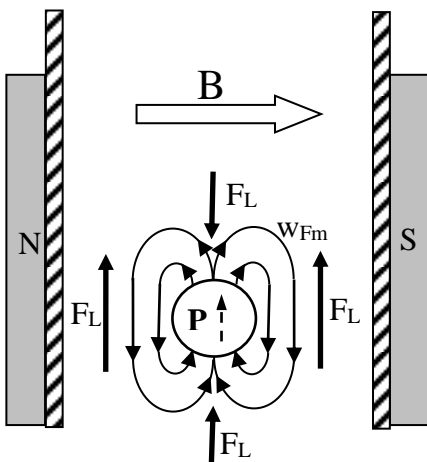
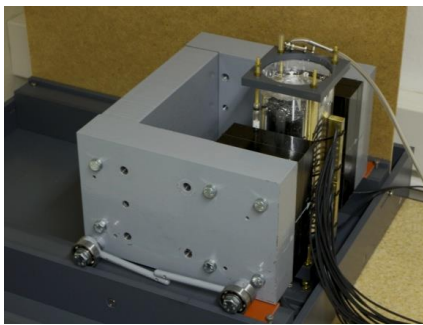
Likewise measurements of rising bubbles in a permanent magnetic field has been done with magnets of average induction  $B = 300$  mT (by Teslameter model 5180). Two magnets 160x100x50 were spaced at 115 mm.

The resultant Lorentz' force in a magnetic field of induction  $B$  equals to:

$$\mathbf{F} = \mathbf{j} \times \mathbf{B} = \sigma_{el} (\mathbf{w} \times \mathbf{B}) \times \mathbf{B} \quad (1)$$

where:  $\mathbf{j}$  – current density,  $\mathbf{w}$  – liquid metal velocity,  $\sigma_{el}$  – electric conductivity.

Drawing no 3 shows the measuring bench container with ultrasonic heads in magnetic field as well as directions and sense of Lorentz' force.

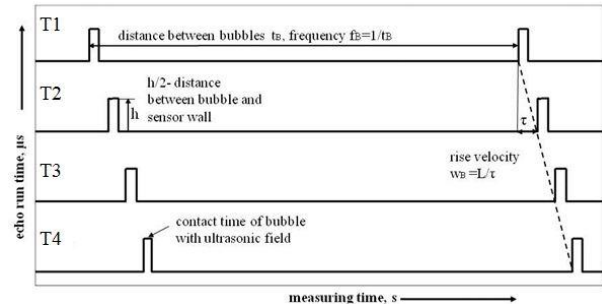


**Fig. 3.** Testing (measuring) bench in a magnetic field and Lorentz' forces acting on liquid metal in magnetic field:  $w_{Fm}$  – liquid metal velocity,  $P$  – gas bubble rising up vertically.

## 4 The results of studies and discussion

### 4.1 Rise velocity of bubbles

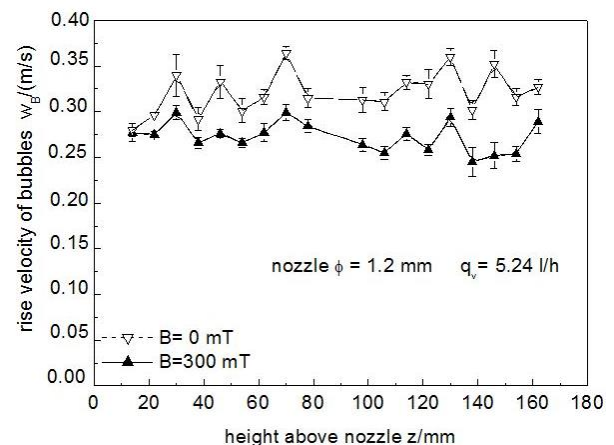
A typical measuring signal of rising bubbles of echo run time method is shown on Fig.4.

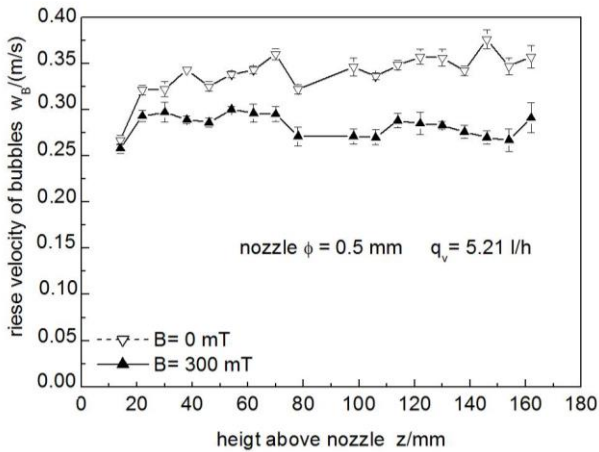


**Fig. 4.** Measuring signal of echo run time method.

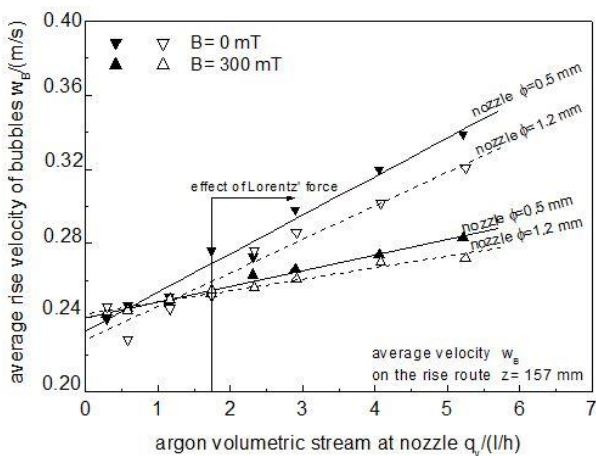
The velocity  $w_B$  of the bubble (vertical component of velocity) was calculated by measuring the bubble time  $\tau$  on the  $L$  road between two successive ultrasonic sensors. Fig.5. shows exemplary results of bubble velocity measurements from the height above the argon inlet nozzle for  $B = 0$  mT and  $B = 300$  mT. Fig.6. shows the dependence of average speed on the flow of argon volume calculated for the condition at the inlet nozzle also for  $B = 0$  mT and  $B = 300$  mT.

Starting from the volume flow of argon at the nozzle  $q_v = 1.8$  l/h, the velocity of the bubbles in the magnetic field is lower than the velocity for  $B = 0$  mT. Differences in velocities are increasing with increasing gas flow. The flow value  $q_v = 1.8$  l/h can be taken as the beginning of the influence of Lorentz force on the velocity of rising bubbles.





**Fig. 5.** Rise velocity of bubbles for  $B = 0$  mT &  $B = 300$  mT.



**Fig. 6.** Rise velocity of bubbles as a function of argon volumetric stream at nozzle.

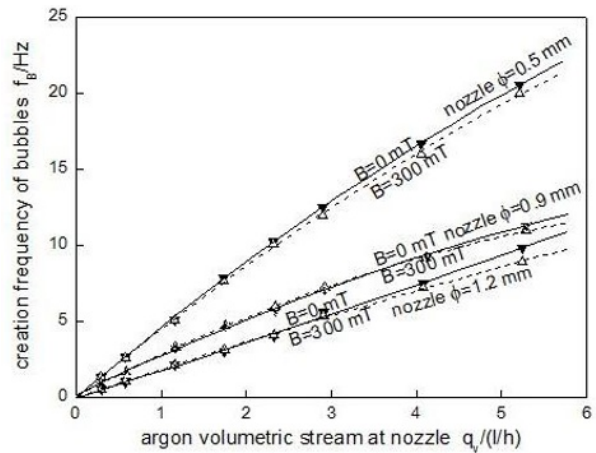
#### 4.2 The creation frequency of bubbles and its dimension

The process of gas bubble creation is difficult to describe theoretically and because of it to estimate the frequency and dimension of bubbles empirical approximate equations are used. The basic equation to calculate the frequency of bubble creation is given in a work [9]:

$$f_B = 3.82 \cdot 10^{-5} \cdot (g^{0.75} \cdot q_v / (d_o^{0.75} \cdot \nu^{1.5})) \quad (2)$$

where:  $\nu$  – kinematic viscosity coefficient,  $q_v$  – gas volumetric stream at nozzle.

The authors of study [10] pointed out that utilization of the above mentioned equation for a nozzle of 0.5 mm diameter and water-air flow gives errors of more than 100%. On a Fig. 7 are presented experimental study results showing a relationship of bubble creation frequency as a function of argon stream volume at nozzle. The results were calculated with Fourier quick transform FFT of measured signal. As the studies shown, in practice a magnetic field does not exert an influence on bubble creation frequency changes.



**Fig. 7.** Creation frequency of argon bubbles as a function of gas volumetric stream at nozzle for  $B = 0$  mT &  $B = 300$  mT.

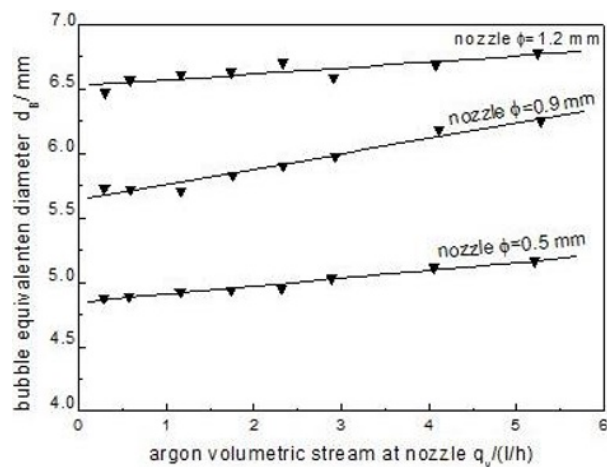
The frequency difference between  $B = 0$  mT and  $B = 300$  mT exists for argon volumetric flow greater than 6 l/h and nozzles of 0.5 & 1.2 mm. Anyhow they does not exceed 10% and seems to be of measurement errors origin. The diameter of rising bubble  $d_B$  is calculated with Mersmann's equate in a form of:

$$d_B = \{3 \cdot \sigma \cdot d_o / (g \cdot \rho) + ((3 \cdot \sigma \cdot d_o / (g \cdot \rho))^2 + (15 \cdot q_v^2 \cdot d_o / g))^{1/2}\}^{1/3} \quad (3)$$

This equate has been delivered on the base of force balance influencing an individual spherical rising gas bubble in motionless liquid. A gas bubbles are introduced into container through a nozzle with a diameter of  $d_o$ , and gas stream rises it up  $q_v$ .

The above given equation were used by Kaiser [5-6] to estimate diameter of rising gas bubbles in mercury, with gas flow stream  $q_v = 3.6$  l/h. From among many others correlation s it is worth to mention Kantarcia [11] equations for calculating diameter of bubbles moving in barbotage columns. On a Fig.8 is presented relationship of bubble average equivalent diameter  $d_B$  on gas volumetric stream for a nozzle  $q_v$ . It is calculated by means of:

$$d_B = (6 \cdot q_v / (\pi \cdot f_B))^{1/3} \quad (4)$$



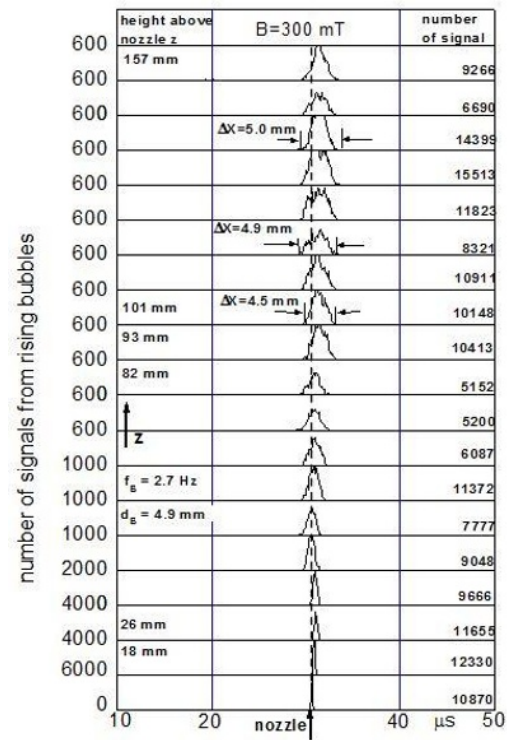
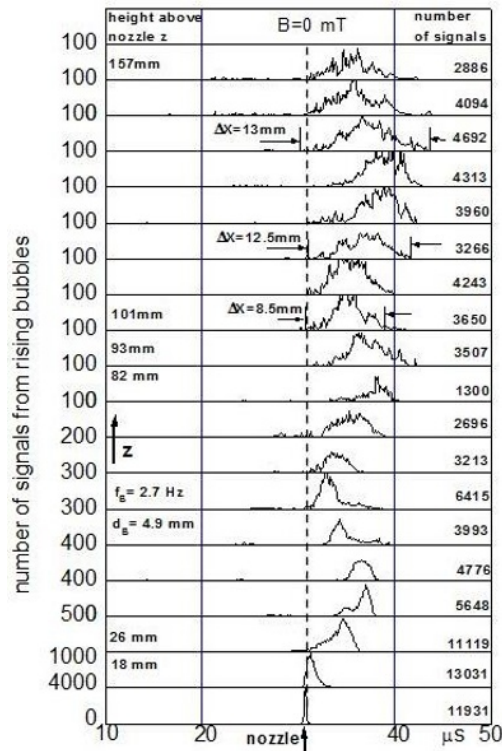
**Fig. 8.** Dependency of bubble equivalent diameter on volumetric gas stream at nozzle.

### 4.3 The gas phase rising zone

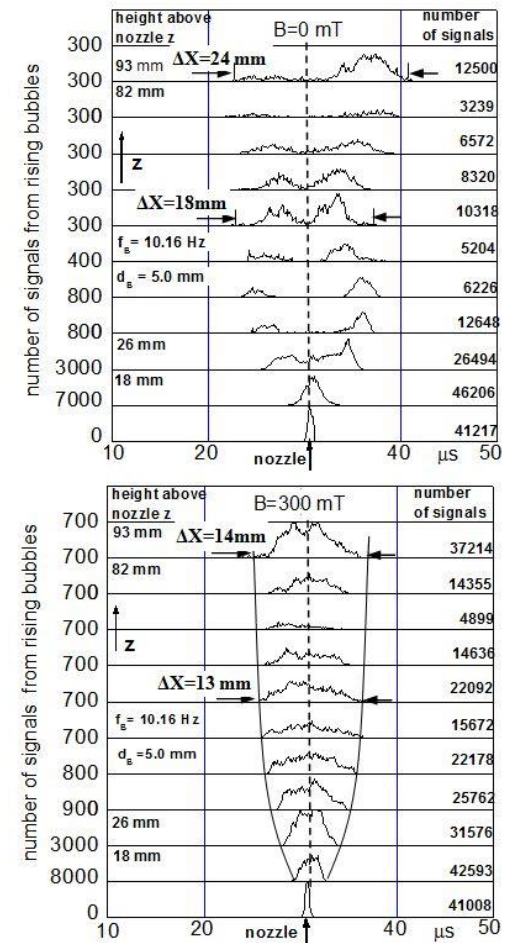
Most of works assigned to estimate a zone inside which a gas phase is present are based on analyzes of flow patterns obtained from model studies of bubble movement or gas stream, most often observe in a water filled container. It was proved by many investigators [12-16] who were studied the phenomenon's. From the practice point of view in estimation of gas phase flow zone the most important are computer tomography methods utilizing mainly capacitance or optical sensors [17-18].

Ultrasonic echo pulse method enables as well estimation of a zone inside which exists gas flow phase likewise in nontransparent fluids as in liquid metals. A knowledge of the flow region is helpful in fixing the best disposition of argon inlet nozzles in steel refining processes.

Drawings no's 9 & 10 present the argon gas rise bubble distribution in a liquid metal along a route  $z = 157$  mm above inlet nozzle for  $B = 0$  mT &  $B = 300$  mT. On the right side is presented the signal quantity of rise bubbles on each measuring level as well as flow zone width  $\Delta X$  on some levels. The measurements has shown, that in magnetic field the argon bubbles rises straightforward and the rise zone is even 50% smaller than the rise zone without magnetic field. It is clearly visible on a Fig.10. where the flow of argon bubbles divides into two streams at  $B = 0$  mT and at  $B = 300$  mT. The flow goes up nearly straightforward with a maximum flow zone width  $\Delta X = 14$  mm. The straight forward movement of bubbles bring forth a greater number of bubbles into the ultrasonic region of measuring sensor as it is salient for regions higher than 82 mm above nozzle. There the number of bubbles found in the ultrasonic field of the sensor is a couple of times greater than in a flow without a magnetic field.



**Fig. 9.** Rising gas bubble distribution for nozzle  $\phi = 0.5$  mm and  $q_v = 0.6$  l/h.



**Fig. 10.** Rising gas bubble distribution for nozzle  $\phi = 0.5$  mm and  $q_v = 2.4$  l/h.

## 5 Summary

The topic of this paper is adaptation of ultrasonic echo pulse method to identify two-phase liquid metal-gas. Apart from using it in defectoscopy the echo method maybe well used in measurements of characteristic parameters of liquid metal-gas flows. In these studies only a time measurement of echo route from moving bubbles method has been utilized as that method characterize the most favorably signal-to-noise ratio as well as an easy and precise definition of bubble position and by that estimation of the flow zone.

The accomplished measurements and its result analyzes allows to state the following conclusions:

- the Lorentz' force reduces the argon bubbles rise velocity in liquid metal of GaInSn; the influence of Lorentz' force on rise velocity begins with argon flow stream of  $q_v = 1.8$  l/h
- a magnetic field does not change the creation frequency of gas phase bubbles therefore the average equivalent diameter of rising bubble has not change
- a proper values of gas phase creation frequency for different inlet nozzle diameters of gas introduced to liquid metal enables the right estimation of rise bubble dimension and by that the proper sizing of nozzle diameters for a specific processes of refining liquid steel
- a decrease of gas bubble rise velocity in a magnetic field increase the contact time of bubbles with liquid metal and in consequence enable the best utilization of blow-in gas
- the magnetic field influence also the bubbles movement trajectory –practically the bubbles rise up straightforward and its flow zone width is smaller than for the rising without the magnetic field; this effect maybe utilized for suitable disposition and selection of distances between argon inlet nozzles in order to obtain the best distribution of gas phase in processes of refinement and degassing liquid metals without forming dead zones in the refining vat.

## References

1. C. Zahng, *Liquid metal driven by gas bubbles in a static magnetic field* (Dissertation, Fakultät Maschinenwesen der Technische Universität Dresden, Dresden, 2009)
2. C. Zhang, S. Eckert, G. Gerbeth, *International Journal of Multiphase Flow* **31** (2005)
3. Z.H.Wang, S.D. Wang, X.Meng, M.J.Ni, *International Journal of Multiphase Flow* **94** (2017)
4. S.Boden, S. Eckert, G. Gerbeth, M. Simonnet, M.Anderhuber, P. Gardin, *(X-ray visualisation of bubble formation and bubble motion in liquid metals. 6<sup>th</sup> Int. Conf. on Electromagnetic Proc. of Materials, Dresden, 2009)*
5. E. Kaiser, *Tm – Technisches Messen*, **71** (2004)
6. E. Kaiser, *Chemie Ingenieur Technik* **76** (2004)
7. H.-D.Sommerlatt, E. Kaiser, *Tm – Technisches Messen* **71** (2004)
8. A. Andruszkiewicz, K. Eckert, S. Eckert, S. Odenbach, *European Physical Journal Special Topics* **220** (2013)
9. H. Brauer, *Grundlagen der Einphasen -und Mehrphasenströmungen* (Verlag Sauerländer, Aarau und Frankfurt am Main, 1971)
10. A. Andruszkiewicz, H.-D. Sommerlatt, *Chemical and Process Engineering* **29** (2008)
11. N. Kantarci, F. Borek, K.O. Ulgen, *Process Biochemistry* **40** (2005)
12. A.Sokolichin, C. Eingenberger, A. Lapin, A. Lübbert, *Chemical Engineering Science* **52** (1997),
13. A.Sokolichin, C.Eingenberger, *Chemical Engineering Science* **49** (1994)
14. Y. Pan, M.P Dudukovic, *AIChE* **46**, (2000)
15. N.G. Deen, T. Solberg, B.H. Hjertager, *Chemical Engineering Science* **56** (2001)
16. A. Tomiyama, I. Zun, H. Higaki, Y. Makino, T. Sakaquichi, *Nuclear Engineering and Design* **175** (1997)
17. 2<sup>nd</sup> International symposium an Process Tomography in Poland 11<sup>th</sup>-12<sup>th</sup> September 2001
18. 4<sup>nd</sup> International symposium an Process Tomography in Poland (Computer Engineering Department Technical University Lodz, September 2004)