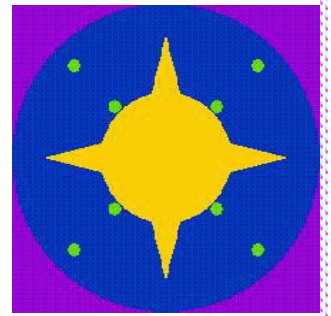


CT 2004



INVITED TALKS

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University of Hannover (Germany)

Impedance Technique for the Measurement of Two Phase Flow Parameters: Possibilities and Challenges

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DPEND, Indira Gandhi Centre for Atomic Research

Steady-state Multi-phase Flow Measurement Facility at FCRI

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Bone Imaging Using Compound Ultrasonic Tomography

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Challenges in quantitative ultrasound bone strength assessment : status and perspectives

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Determination of 3-D Concentration Field around a Growing Crystal Using Laser Shadowgraphic Tomography

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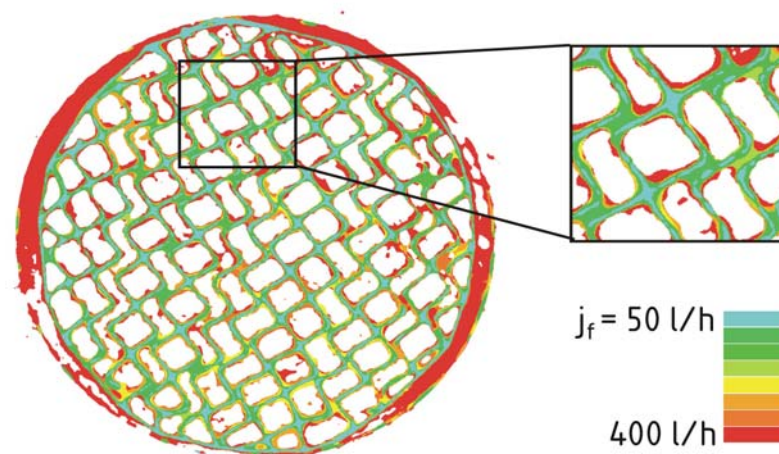
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Process Tomography: Development and Application of Non-intrusive Measuring Techniques for Multiphase Flows

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The variety of ready to use measuring techniques available on the market is ever growing. But nevertheless in multiphase flows the non-intrusive acquisition of local measurements of process parameters like temperature, concentration or volume fractions often is still a challenge. In many cases instead of the desired local measurements only integral measurements, for instance along lines, can be obtained. This is the point when process tomography comes into play. In general, in tomography the desired local values of the respective property are reconstructed mathematically from a certain number of integral measurements. Depending on the measurement task, a variety of optical, electrical conductance, electrical capacitance, X-ray, and some other can be used. The various techniques differ significantly in their suitability for different measurement objects, spatial and temporal resolution, and availability on the market, cost, and many more parameters. In process engineering research the desired tomographic systems often are still not offered commercially. The Institute of Process Engineering of the University of Hannover, Germany, looks back on many years of developing, building and using its own tomographic systems, covering all the above mentioned techniques. This presentation gives an overview of the tomographic measuring systems built and used at the Institute of Process Engineering and the research work they are applied for.



X-ray tomography (CT): Liquid film in packing depending on flow rate

Impedance Technique for the Measurement of Two Phase Flow Parameters: Possibilities and Challenges

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1. Introduction

Multiphase flow or simultaneous flow of several phases is commonly encountered in a variety of engineering processes. Simultaneous flows of as many as four phases namely, water, crude oil, gas and sand is not uncommon during oil exploration though flow of two-phase mixtures is the most common occurrence in industry. Simultaneous flow of gas and liquid or gas liquid two phase flow is observed in power generation, refrigeration and cryogenics as well as in chemical process industries.

In spite of the extensive volume of past research activity, two phase flow is not yet an area in which theoretical prediction of flow parameters is generally possible. Indeed, this situation is likely to persist for the foreseeable future. Thus, the role of experiment and parametric measurement is particularly important.

The techniques of measurement for single-phase flow are well established. Based on these techniques, various meters and instruments have been developed which are successfully employed for industrial measurement as well as for R&D activities. Unfortunately, these instruments cannot be directly used for multiphase flow measurement. Most of the problems in multiphase flow measurement arise from the fact that the parameters characterizing it are many times larger than those in single-phase flows. In single-phase flow, the flow regimes encountered are laminar, turbulent and a transition region between them. In multiphase flow, numerous flow regimes are possible. The flow regimes observed under a specific set of flow conditions is dependent on flow geometry (size and shape) and orientation (vertical, horizontal and inclined), flow direction in a vertical or inclined flows (up or down), phase flow rates and properties (density, viscosity, surface tension). It may be noted that the flow regimes change drastically from the adiabatic case when phase transition (due to heat transfer) is involved. In general, the following features, which complicates the flow situation may be identified:

1. Even for the steady flow rates of the phases at the inlet, the local flow phenomenon may become intermittent.
2. The distribution and velocity of the phases may change both with space and time.
3. In case of phase change, the flow regimes vary substantially along the flow direction. It may also be appreciated that unlike the single-phase flow there are some unique parameters in two-phase flow, which needs to be measured. For example, as the hydrodynamics depends largely on the prevailing flow regime, it has to be identified and the void fraction or the phase fraction (amount of a particular phase in a given cross section or volume) is to be determined. In certain

applications parametric valued of each of the phased (namely phase velocity or phase flow rate) need to be predicated.

This has given rise to the development of a number of techniques especially suited for the measurement of two-phase flow parameters. As often one has to measure the parameters separately for both the phases one needs to exploit a property, which has grossly different values for the phases at the condition of measurement. Based on this logic, measurement techniques have been developed using optical, radiation attenuation acoustic and impedance principle. In the present paper measurement technique based on impedance principle will be elaborated.

As the electrical impedance of a two-phase mixture is a function of concentration, measurement of impedance can form a basis for the estimation of different two phases. Several instruments for the measurement of void fraction and associated parameters have been developed based on impedance technique has the following advantages:

1. It is a low cost technique.
2. It is suitable for transient measurement.
3. Large variations of electrode design are possible making the method appropriate for different flow situations and geometry.
4. Both intrusive and non-intrusive measurements are possible.
5. Point measurement as well as global measurement can be made by suitable design of the probe.
6. Same principle (sometimes the same probe) may be used for the measurement of associated parameters like,
 - a) flow regime identification,
 - b) bubble size and frequency
 - c) bubble velocity.

An impedance probe can be designed such that the prediction is made either due to the variation of capacitance. If the liquid phase is the continuous one and electrically conduction, then the probe is used in the resistive mode. If the gas phase is continuous or the liquid phase is non-conduction, then the probe is used in capacitance mode. A large variety of probe design is possible some of them are described below.

2. Separated flow of gas and liquid

In annular flow, stratified flow, film flow, the gas and liquid phases are separated by a well defined interface and generally the liquid phase does not contain any gas bubble in dispersed condition. In such situation, impedance probe gives a good estimate of the liquid film thickness. From electrostatics one gets,

$$\nabla^2 V = 0 \tag{1}$$

$$E = -\nabla V \tag{2}$$

$$J = \epsilon E \tag{3}$$

From Ohm's Law,

$$J = \iint_s J ds \tag{4}$$

and

$$R = 2V_1 I \tag{5}$$

Where V is the electrical potential, J the current density, E the electrical field, I the current, σ the conductivity of the liquid and R the resistance.

Finally, the current I can be expressed as

$$I = L\sigma \int_{-0/2}^a E_r(R_1 d\Phi) \quad (6)$$

From the above relationships, one can calculate the resistance for a given liquid height and liquid conductivity.

$$R = |V_{in} / V_0| R_f \quad (7)$$

Using the above relationships one can determine the void fraction for different separated flow conditions.

3. Homogeneous mixed flow of gas and liquid:

Impedance probes can also be used when the phases are well mixed (bubbly flow or drop flow). When the phases are well mixed from Maxwell's theory, one gets

$$\alpha = \frac{A - A_c}{A + 2A_c} \cdot \frac{\epsilon_G + 2\epsilon_L}{\epsilon_G + \epsilon_L} \quad (8)$$

Where A_c is the admittance of the gauge when immersed in the liquid phase alone. ϵ_G and ϵ_L are the conductivities of the gas and liquid phases if conductivity is dominating. On the other hand, one should use the dielectric constants if capacity is important. The above equation is suitable for bubbly flow.

For liquid droplet flow through a gas, one gets

$$\alpha = 1 - \frac{(A\epsilon_L - A_c\epsilon_G)}{(A\epsilon_L + 2A_c\epsilon_G)} \cdot \frac{(\epsilon_L + 2\epsilon_G)}{(\epsilon_L - \epsilon_G)} \quad (9)$$

4. Types of probes:

Depending on the requirement of measurement probe, different geometries have been developed. Probes based on resistance or conductance principle generally have the electrode in direct contact of the conducting phase. They can either be inserted in the flow cross-section or may be flush mounted on the inside wall of the conduit.

For probing into an area or a volume an arc type, ring type, parallel wire and parallel plate electrodes are commonly used. Conductivity or resistivity probes can be designed to probing into a very small area idealized as a point. This is done by a needle contact probe. With the help of traversing mechanism it can give the void age profile. Increasing the number of the needle contacts (2 to 4) determination of the bubble size and bubble velocity is possible. Capacitance probes on the other hand are mounted on the outer surface of the conduit and have limited options as far as geometry is concerned. They are made of arc and spiral shape.

5. Challenges in the impedance based measurement

i) **Estimation of void fraction:** As the probes operate neither purely in the capacitance mode nor in the resistance mode theoretical modeling becomes difficult.

- ii) **Fringing effect:** This results in three-dimensional effects in area probes and induces error. In conductivity probes and induces error. In conductivity probes this can be reduced by guard electrodes. The size of the capacitance probes needs to be determined to reduce the fringing effect.
- iii) **Stray capacitance effect:** As the change of capacitance due to the change of phase fraction is less the circuit has to be designed properly to reduce the stray capacitance effect.
- iv) **Property variation:** The change of conductivity and dielectric constants due to impurity, temperature change is also another concern.
- v) **Double layer effect:** This is one of the least understood phenomena, which plays a very important role in the performance of the impedance probe. With the existing information it is extremely difficult to model the effect of double layer. However by suitable design of the probe and adoption of experimental technique this effect can be reduced. In the full-length paper it will be discussed in detail.

Ultrasonic Assessment of the Effect of Variations of Different Process Parameters in Blowing of Industrial Rubbers

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Ultrasonic non-destructive evaluation techniques are widely used for flaw detection purposes. With modifications, the techniques can also be used to characterize different physical and chemical processes. One such recent example is the ultrasonic monitoring and characterization of the blowing process of industrial rubbers in which the monitoring, done in real time, is more effective than the existing techniques employing rheometers and gas-capturing-processibility-testers. Blowing in rubber is the process of dissolution of the constituent chemical agents causing formation of numerous bubbles. The presence of numerous bubbles in blown rubbers leads to the cellular structure of the product and these materials, having comparatively lower stiffness, are suitably used as surface layer of the printing rolls and in other weather stripping applications. A computer controlled ultrasonic NDE facility has been devised to perform ultrasonic measurements on a blowing sample. Definite ultrasonic signatures in the form of signal amplitude and time-of-flight variations are found to exist in detection of blowing.

The bubble formation process is, however, complex and may be affected by several factors. Important factors include (i) the temperature at which the rubber is heated, (ii) types and properties of the chemicals being used as blowing agents and (iii) the extent of the natural cure present in the rubber. In the present case studies, effects of the first two factors on ultrasonic signatures are taken into consideration. The heating temperature seems to have a direct effect on the rapidity of the blowing process and such effects can be suitably studied by the observing changes in the said ultrasonic signatures. Three different temperatures namely 160°C, 180°C and 200°C have been used for the study. Ultrasonic signal amplitudes and time-of-flight at discrete time intervals are recorded during measurement and their variation signatures are considered for possible correlation with the blowing process. Observations are compared with the respective photomicrograph of the cross-sections of the blown sample.

Rapidity of blowing also depends on the composition of chemical agents. Such a case study has also been performed on rubber samples with three different blowing agents and ultrasonic signatures have been found to be adequately sensitive to the corresponding rate of blowing.

X-Ray Computed Tomography for Solid Objects

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Computed Tomography (CT) has proved to be one of the powerful tools for internal structure visualization in Non-Destructive evaluation of objects in industrial and scientific applications. Tomography is an imaging technique, which produces cross sectional details of an object from its line integrals of projections. The design of the CT machine for industrial and scientific applications is more complex than medical systems since, it has to accommodate large variations in density and achieve finer resolution. The tomography system at the author's laboratory consists of an X-ray source, manipulator for object handling and a image intensifier based real time system. The X-ray unit is Eresco 200 MF with a voltage range of 20-200 kV and a maximum tube current of 10 mA. A 9 inch trifold image intensifier has been used. This tube with CsI screen has a typical resolution of 45 lp/cm in normal mode and 65 lp/cm in the magnification 2 modes. The critical part of the tomography system is the source, detector and object-handling units. Both the X-ray tube and the detector are mounted on a 'C' arm so that alignment of the source and detector becomes relatively simple. The object is held in a precision manipulator designed and developed indigenously. This is a four-axis manipulator capable of handling objects with a maximum weight of 25 kg. The span in the x, y and z directions are 30, 25 and 15 cm with step resolution of 10 micron and the resolution in θ is 0.001 degree. The manipulator is controlled by PC card. Data acquisition is accomplished using an 8bit frame grabber card and the data are captured and analyzed using a PC. As a first step, objects with regular shapes and standard artificial defects were designed and evaluated to standardize on the methodology, software and also establish the limits of detectability and contrast sensitivity. The objects were:

- (1) 25 mm Aluminum cylinder,
- (2) 25 mm Aluminum cylinder with 3 mm central hole,
- (3) 25 mm Aluminum cylinder with 3 mm central hole filled with Steel &
- (4) 25 mm Aluminum cylinder with 3 mm central, 3 mm off central and 4 mm off central holes.

400 projections in 360 degree were acquired. The reconstruction of the images has been done using Filtered Convolution Back Projection technique. The correction for polychromaticity of the beam has been done using beam hardening technique. The details of data acquisition and reconstruction are discussed. The density matrices of the images obtained are close to actual object. The size of the object and the holes are predicted with an accuracy of about 8 %. The systematic approaches to be followed, the important points to be considered and the difficulties that may arise during the setting up of a optimum and reliable industrial CT setup for NDE applications would be specifically highlighted from the experience of the authors.

Further, a setup for microtomography using cooled CCD and microfocus X-ray source is under progress. The arrangement for the same will also be discussed.

Steady-state Multi-phase Flow Measurement Facility at FCRI

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Multi-phase flow, gas-liquid two-phase flow in particular, is of critical importance to industries in Oil and gas sector and Nuclear power plants. Measurement of multi-phase flow is not easy and the methods currently in use are particularly not very accurate. Uncertainties of unacceptably high order have been reported when conventional single-phase flow meters such as turbine-meters, mass flow meters are attempted for multi-phase flows. Extreme variations in viscosity, density and velocity between the phases occur not only across the pipe but also temporarily along the pipe. Much care has to be taken for properties of the different fluids when metering multi-phase fluids. The past three decades have witnessed considerable progress in development of technologies for measurement of phase-fraction and two-phase and three-phase flow measurement

As part of a BRNS-sponsored project, FCRI designed and developed a multi-phase flow-meter using gamma-ray attenuation technique in conjunction with Venturi-meter. A Test Facility to evaluate performance of the developed multi-phase flow meter was also set-up at FCRI. This paper describes the multi-phase hydraulic test facility and the performance / behaviour of the multi-phase flow meter under various test flow-regimes.

Bone Imaging using Compound Ultrasonic Tomography

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The goal of Ultrasonic Tomography is to reconstruct the spatial distribution of some acoustic parameter of an object using ultrasonic measurements. The measurements are made for a set of emitter-receiver positions and of frequencies of the interrogating wave. The method is based on a linear approximation of the inverse scattering problem, the Inverse Born Approximation (IBA), which allows to reconstruct small perturbations from a known-reference medium.

For media with weak inhomogeneities, such as soft biological tissues (weak scatterers), the method works straightforward. This leads to a "Constant Background" IBA method, whose practical solution results in regular angular scanning with broad-band pulses, allowing to cover slice-by-slice the spatial frequency spectrum of the imaged object. This leads to "Reconstruction-From-Projections" algorithms like those used for X-ray Computed Tomography.

For media with strong heterogeneities as bone (strong contrasts, large objects with respect to wavelength), the problem is non-linear and there is in general no single solution. In this case, ultrasound tomography suffers from an important limitation due to strong wavefronts distortion (refraction, attenuation) resulting in a poor quality of tomographic images.

One solution is to compensate for refraction based on an exact *a priori* knowledge of the geometry and of the speed of sound of the object and on the assumption that the Snell's law is valid for each single ray. The exact shape and size of the test object can be reconstructed from initial measurements performed using Ultrasonic Reflection Tomography. Ultrasonic Transmission Tomography, using compensation procedure, provides then quantitative values of the sound velocity. In case of inaccurate *a priori* object size and sound velocity, the algorithm becomes an iterative process, which converges quickly towards the solution.

Preliminary experimental results on human femur demonstrate the feasibility of quantitative images using Compound Ultrasonic Tomography.

Challenges in Quantitative Ultrasound Bone Strength Assessment : Status and Perspectives

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Because ultrasonic waves involve compressional or shear stress, the propagation characteristics of ultrasonic wave through bone are closely related to its mechanical properties (elastic constant) as well as to any other bone characteristics, such as bone mineral density, micro-architecture or micro-damages relating to mechanical properties. Quantitative ultrasound (QUS) measurements is playing a growing role in the assessment of skeletal status. Currently available technologies are based on measurements in transmission of the slope of the frequency-dependent attenuation and the speed of sound at peripheral skeletal sites (finger phalanges, heel, wrist). In this contribution, we will review the current state of development and we will outline a few promising developments.

Several investigations are currently being conducted to develop innovative QUS techniques, such as transmission imaging technology, reflection techniques based on backscatter, propagation of guided waves along cortical bone and ultrasound tomography. The feasibility of these different approaches and / or their clinical evaluation is currently being studied in different groups.

In contrast to X-ray based computed tomography which is a well-established technique in osteoporosis diagnostics, quantitative ultrasound tomography is still in its infancy and raises new challenges. In particular, an accurate interpretation of ultrasound measurement requires first a detailed understanding of ultrasound propagation with clear identification of the different waves and their exact propagation path that contribute to analyzed signals. In other words, this requires solving the direct problem. Analytic solutions become rapidly inextricable due to the complexity of the medium. The situation is progressively being changed, with recent development of numerical tools based on finite difference modeling that permits to accurately model the propagation of ultrasound wave in 3D anisotropic models of bone. Numerical simulations can be performed on actual bone geometry, as measured from 3-D X-rays computerized tomography (CT) for instance, combined with local effective elastic constants. Such computations have recently been able to elucidate the propagation of ultrasound in cortical bone. Another powerful advantage of these simulation tools is their potential to explore virtually different experimental configurations to measure bone properties (i.e., tomography) and therefore to guide engineers to design novel techniques for *in vivo* bone strength assessment.

Computerized Tomography in Blast Furnace

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Many experimental studies have been carried out to study the workings of packed bed Reactors such as Blast Furnace, Catalytic Reformer and Solid drying Process using various two/three dimensional models. Blast Furnace is the most complex and typical among them. However, no experimental data are available in the literature on the estimation of permeability distribution in a packed bed, which is very essential and important to understand the dynamics of the packed bed reactors.

The focus of this topic is to reconstruct three-dimensional image from two dimensional image slices obtained from X-Ray Radiography System. This will help us in the estimation of permeability distribution in a packed bed

The systems involving X-Ray, Gamma Ray, Ultrasonic, Eddy Current etc. are principally used in Non-Destructive Testing. Most of the methods used in those systems can be combined into the mathematical techniques of Computerized Tomography (CT). The mathematical techniques used are based on Convolution Back Projection Algorithm (CBP).

Electrical Tomography for Two-Phase Flows: “Seeing without eyes inside stirred vessels”

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Body scanning exploiting 3-D imaging has revolutionised diagnostics and treatment in medicine. Process engineers would like to be able to image chemical process units in 3-D, but without the £multi-million price tag. UMIST has pioneered several electrical process tomography techniques and used them for a variety of applications. Illustrations are presented to show how electrical resistance tomography has been developed for typical stirred vessels widely used in chemical process manufacturing especially as chemical reactors. The technique is potentially fast and inexpensive and capable of 3-D imaging both dynamic and pseudo-stationary processes. Examples for UMIST’s 2-tonne vessel will be presented for miscible tracer mixing as well as gas-liquid and liquid-solid mixing.

A list of recent references by the author is attached.

References

R. Mann with M. Wang, F. J. Dickin, T. Dyakowski, P. J. Holden and A. E. Forrest, "Resistance Tomography Imaging of Stirred Vessel Mixing at Plant Scale", I. Chem. E., Symp. Series, 140, 155, 1996

R. Mann with F.J. Dickin, M. Wang, T. Dyakowski and R.A. Williams, "Application of Electrical Resistance Tomography to Interrogate Mixing Processes at Plant Scale", Chem. Eng. Sci., 52, 2087, 1997

R. Mann with R.A. Williams, T. Dyakowski, F.J. Dickin and R.B. Edwards, "Development of Mixing Models using Electrical Resistance Tomography", Chem. Eng. Sci., 52, 2073, 1997

R. Mann with M. Wang "Recent Developments in Electrical Techniques for Chemical Process Tomography", Meas. and Control, 30, 206, 1997

R. Mann with P.J. Holden, M. Wang, F.J. Dickin and R.B. Edwards, "Imaging Stirred Vessel Macro-Mixing using Electrical Resistance Tomography", AIChE JI., 44, 780, 1998

R. Mann with P.J. Holden, M. Wang, F.J. Dickin and R.B. Edwards, "On Detecting Mixing Pathologies Inside a Stirred Vessel Using Electrical Resistance Tomography", Trans. I.Chem.E 77 (A), 709, 1999

R. Mann with P.A.T Pinheiro, W.W. Loh, M. Wang and R.C. Waterfall, "Three-Dimensional Electrical Resistance Tomography in a Stirred Mixing Vessel", Chem. Eng. Comm., 175, 25, 1999

- R. Mann with M. Wang and F.J. Dickin "Electrical Resistance Tomography Sensing Systems for Industrial Applications", Chem. Eng. Commun., 175, 49, 1999
- R. Mann with M. Wang, A.E. Forrest, P.J. Holden, F.J. Dickin, T. Dyakowski and R.B. Edwards, "Gas-Liquid and Miscible Liquid Mixing in a Plant-Scale Vessel Monitored Using Electrical Resistance Tomography," Chem. Eng. Commun., 175, 39, 1999
- R. Mann with D.S. Vlaev, M. Wang, T. Dyakowski and B.D. Grieve, "Detecting Filter-Cake Pathologies in Solid-Liquid Filtration: Semi-Tech Scale Demonstrations using Electrical Resistance Tomography (ERT)", Chem.Eng.Jl., 77, 87, 2000
- R. Mann with M. Wang, A. Dorward and D.S. Vlaev, "Measurements of Gas-Liquid Mixing in a Stirred Vessel using Electrical Resistance Tomography", Chem.Eng.Jl., 77, 93, 2000
- R. Mann with T. Dyakowski, M. Mikos, D.S. Vlaev, G.W. Follows, A. Boxman and M.P.W. Wilson, "Imaging Nylon Polymerisation Processes by Applying Electrical Tomography", Chem.Eng.Jl., 77, 105, 2000
- R. Mann with E. Yuen, S.D. Vlaev, T. Dyakowski, B.D. Grieve and T.A. York, "Applying Electrical Resistance Tomography (ERT) to Solid-Fluid Filtration", Proc of 8th World Congress on Filtration, 165, 2000
- R. Mann with M. Rahimi, M. Buchmann and D. Mewes, "Interpretation of macro- and micro-mixing measured by dual-wavelength photometric tomography", Proc. 10th Europ. Conf. on Mixing, Delft, 377, 2000
- R. Mann with S. Stanley D. Vlaev, E. Wabo and K. Primrose, "Augmented-reality visualisation of fluid mixing in stirred chemical reactors using electrical resistance tomography (ERT)", JI Electronic Imaging, 10(3), 620, 2001
- R. Mann with K. Salem and K. Kling, "Application of Electrical Resistance Tomography (ERT) to Monitor a Flow-Follower in a Stirred Vessel" Proc. 2nd World Congress on Industrial Process Tomography, Hannover, 159, 2001
- R. Mann, with S.J. Stanley, E. Wabo and K. Primrose, "Dual-Validation of Miscible Liquid Mixing in a Stirred Vessel Imaged by Electrical Resistance Tomography (ERT)", Proc. 2nd World Congress on Industrial Process Tomography, Hannover, 151, 2001
- R. Mann with E.L. Yuen, T.A. York and B.D. Grieve, "Electrical Resistance Tomography (ERT) Imaging of a Metal-Walled Solid-Liquid Filter", Proc. 2nd World Congress on Industrial Process Tomography, Hannover, 183, 2001
- R. Mann with S.J. Stanley and K. Primrose, "Tomographic imaging of fluid mixing in 3-D for single-feed semi-batch operations of a Stirred Vessel, Trans.I.Chem.E., 80(A), 903, 2002

Digital Radiography: Imaging and Visualization for Industrial Applications

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Digital radiography (DR) technique is rapidly expanding in industrial and medical applications due to the benefit of cost and productivity it offers in comparison to the traditional film-based radiography. Availability of instant high quality digital radiographic images helps in quick inspection, transmission over network, archiving information in minimal space and the availability of sophisticated image processing algorithms for analyzing the data. Digital radiography along with micro-focal x-ray tube can easily outperform the film-based radiography for several applications. Digital radiography has already established its superior performance by higher dynamic range, better Detective Quantum Efficiency (DQE) and contrast resolution. In addition to its performance the advent of digital radiography technology is promising to create a radiation safe atmosphere since required contrast resolution can be achieved through lower radiation dose. This is a major advantage for medical applications.

The technology of the digital detectors and their performance for industrial radiographic inspection will be discussed with examples. Since the traditional image quality metrics are not sufficient to study the performance of digital detectors, we need a metric, which can completely characterize the digital systems. Characteristics such as Limiting spatial resolution (LSR) and Modular Transfer Function (MTF) can no longer be considered as complete image quality metric for x-ray system's inspection ability. The use of DQE, which is a measure of the combined effect of noise and contrast performance of an imaging system, is a more accurate metric to quantify the performance. DQE comparisons for film and digital detectors will be presented. Some image processing tools that have been developed to analyze the digital radiographs and visualization of CT data will also be discussed.

Convection in Differentially Heated Air-water Layers and its Reconstruction using Radial Tomography in a Circular Cavity

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Buoyancy-driven convection in a differentially heated gas-liquid layer that is confined in a cavity has been experimentally studied. The gas phase is air, while water has been employed as the liquid medium. The apparatus is octagonal in plan that closely approximates a circular cavity. It has a nominal diameter of 130.6 mm and a height of 50 mm. The fluid layer thicknesses have been kept equal at 25 mm in the present study. The lower surface of the cavity is at a higher temperature compared to the top surface. Thus the temperature difference applied in the vertical direction is destabilizing, leading to convection patterns in the fluid phases. The flow and thermal fields in the cavity have been imaged using a Mach-Zehnder interferometer. The flow field in the circular cavity has been scanned through four different view angles namely 0, 45, 90, and 135° for generating the projection data. The projection data was utilized in reconstructing the three-dimensional temperature field using radial tomographic algorithm.

Important applications of flow and heat transfer in superposed fluid layers can be found in buoyancy-driven convection in stratified water bodies such as a solar pond, encapsulated crystal growth from its melt and growth of optical crystals from the aqueous solution. The data from large aspect ratio experiments can be applied to study earth's mantle convection. Recent literature on the subject can be found in the references and has been extensively discussed by Punjabi (2002).

The objectives of the present work are to examine the axisymmetry of the thermal field, three dimensionality and unsteadiness in the convection patterns in the respective fluid layers. The movement of interface with respect to time at higher Rayleigh numbers has also been addressed.

For the temperature field measurement in the fluid medium, the primary instrument employed in the present work is the Mach-Zehnder interferometer. It employs a 35 mW He-Ne (Spectra Physics) laser with 150 mm diameter optics. Interferograms have been recorded using a Pulnix CCD camera with a 512 × 512 pixel resolution. The camera is interfaced with an IBM-compatible PC through an 8-bit A/D card, which digitizes light intensity levels over the range of 0-255. For measurements in liquids, a reference chamber is required to be included with the interferometer to compensate for refractive changes under isothermal conditions. Temperatures at various points over the solid surfaces of the cavity as well as the ambient temperature have been monitored by 18 gage K-type thermocouples that are connected to a San-Ei 30 channel recorder.

The experiments have been performed in the infinite fringe setting of the interferometer. The alignment of the interferometer in the infinite fringe setting is required to be carried out individually for the fluid phases to capture the interferograms. For this purpose, the reference chamber, as in the test cell is also filled

with fluid layers of equal thickness. The reference chamber is however thermally inactive. When a thermal disturbance is introduced in the path of the test beam, fringes appear in the field-of-view. The fringes represent contours on which the path integral of the temperature field along the direction of the light beam is a constant.

Results on two-layer convection in the cavity containing air-water layers are presented in the following discussion. The heights of fluid layers in the experiments were maintained equal at 25 mm. Experiments were conducted with four temperature differences namely 6.5, 8.5, 13, and 18 K in a thermally destabilizing configuration. View angles of 0, 45, 90, and 135° have been considered. The experimental data has been interpreted to understand the influence of increasing Rayleigh number on transition to three dimensionality and unsteadiness.

For the temperature difference of 6.5 K across the cavity, the individual Rayleigh numbers on the air and waterside can be calculated to be 9,530 and 48,474 respectively. The fringe patterns at different view angles appeared similar in terms of orientation, number of fringes and the fringe spacing. Owing to similarity of fringe patterns obtained with respect to the view angle, the thermal field is expected to be axisymmetric. With an increase in the temperature difference to 8.5 K, the thermal field in the cavity was found to be two dimensional in air and three dimensional in water.

The transient evolution patterns at 0° and 90° view angles for the temperature difference of 13 K has been studied. The corresponding Rayleigh numbers in air and water are 18,870 and 1.16E+05 respectively. The flow field in the cavity was found to reach a dynamic steady state after around 2.5 hours.

Tomographic reconstruction shows the loss of symmetry in the thermal field, in particular in water at higher Rayleigh numbers. The reconstruction also shows a plume structure near the axis of the cavity.

REFERENCES

- (1) Zeren, R.W., and Reynolds, W.C., 1972, "Thermal instabilities in two-fluid horizontal layers," *J. Fluid Mechanics*, Vol. 53, No. 2, pp. 305-327.
- (2) Andreck, D.C., Colovas, M.M., and Peter, W.D., 1996, "Observation of time-dependent behaviour in the two-layer Rayleigh-Benard system," *Proceedings of the third Microgravity Fluid Physics Conference*, pp. 313-318.
- (3) Prakash, A., and Koster, J.N., 1997, "Steady natural convection in a Two-Layer system of Immiscible liquids," *Int. J. Heat and Mass Transfer*, Vol. 40, No. 12, pp. 2799-2812.
- (4) Johnson, D., Narayanan, R., and Dauby, P.C., 1999, "The effect of air height on the pattern formation in liquid-air bilayer convection," *Fluid Dynamics at Interfaces*, Cambridge University Press, Cambridge, pp. 15-30.
- (5) Mishra, D., Muralidhar, K., and Munshi, P., 1999, "Interferometric study of Rayleigh-Benard convection at intermediate Rayleigh numbers," *Fluid Dynamics Research*, Vol. 25, No. 5, pp 231-255.
- (6) Gebhart B., Jaluria Y., Mahajan R.L., and Sammakia B., 1988, *Buoyancy-Induced Flows and Transport*, Hemisphere Publishing Corporation, New York.

- (7) Herman, G. T., 1980, Image Reconstruction from projections, Academic Press, New York
- (8) Munshi, P.,1997, Application of Computerized Tomography for measurements in Heat and Mass Transfer, Proceedings of the 3rd ISHMT/ASME HMT conference, IIT Kanpur.
- (9) Punjabi, Sunil, 2002, Experimental study of convection in differentially heated fluid layers using laser interferometry, Ph.D thesis, IIT Kanpur, India.

Tomography in Fusion Plasma Research

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Tomography has demonstrated its usefulness to diagnose fusion plasmas. Its non-invasive character has made it attractive in plasma physics. It is essentially a technique to recover the three dimensional distribution from the measured line integral projections through a mathematical integral transform like Abel transform. Many plasma diagnostics are made capable of measuring line integrals of plasma parameters for tomographic purpose. Some commonly used techniques are Microwave interferometer, Faraday rotation, electron cyclotron emission, visible, ultraviolet, and x-ray emission etc. These diagnostics are used to study plasma properties, like equilibrium, stability, plasma-wall interaction and impurity content, MHD phenomenology, particle and energy transport and turbulence in the plasma core. In fact, tomography has revolutionized the field of plasma diagnostics and has lots of promise for the future fusion experiments.

Tomographic Reconstructive Techniques for Void-fraction distribution in Heavy Density Liquid Metal Two-phase Flows

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Heavy-density molten liquid metals lead, Lead-Bismuth-Eutectic (LBE) and mercury have been proposed as spallation target for neutron source with gas driven circulation of these targets. To design these systems, it is required to understand two-phase high-density flows under various regimes and develop suitable CFD codes, which are validated with experimental data. The two-phase flow regimes (bubbly, Churn, Slug) are governed by void fraction distribution and the accurate determination of void fraction in these systems is complicated in view of high-density, opacity.

A 6.5 m high mercury facility has been set up in our institute to study two-phase nitrogen and mercury flows at ambient temperature. The flow is upward and co-current. The loop consists of mixer, riser, separator, downcomer, MHD flow meter and an MHD generator, dump tank etc. The flow circulation is achieved by creating two-phase flow in the riser. The flow regime obtained in the facility (bubbly and Churn) is similar to the flows expected in the gas-driven spallation targets. A maximum of 60 kg/s mercury flow rate has been achieved.

We have also developed an non-intrusive 7-beam (Fan beam) and a parallel beam void fraction measurement systems based on high-energy gamma rays (Co^{60} of 100 mCi source) for these flows. The attenuation of these gamma rays, which are passed across the cross section of the flow area are measured under three conditions: when the pipe is filled with mercury, when filled with nitrogen and when there is a two-phase flow present. The data is collected at different orientations by rotating and parallel displacement of the source and detectors.

We have studied in detail many variants of ART (Algebraic Reconstruction Technique) and MART (Multiplicative Algebraic Reconstruction Techniques) algorithms for reconstruction of void fraction distribution. All these algorithms were tested by comparing with predicted values of simulated void fraction distribution. In general MART algorithms were better suited than ART for void fraction reconstruction for heavy density two-phase liquid metal flows.

In this talk, details of the experimental loop, void fraction measurement system and various ART and MART tomographic algorithms used will be presented along with measured void fraction profiles for a typical flow.

3D Tomography using Neutrons and x-rays

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3D Visualization of the interior of an object has been one of the important goals of NDT. It can be used for examination of defects and cracks in their full three dimensional perspective and for reverse engineering applications. Such a goal of 3D visualization can be realized using tomography techniques. Both neutron and x-rays have been used for such a purpose each with its own unique properties and area of application. However, most of the applications on neutron and x-ray tomography have been developed to provide only 2D cross-sectional image of the object. Extending such 2D tomography technique to 3D tomography has its own problems and limitations. One of the methods used in such 3D visualization involves obtaining several two dimensional tomography scans at different positions of object and then combining these images into a three dimensional volume data. Volume rendering or surfaces rendering techniques are then used for visualization of such volume data. While the other method involves direct 3D reconstruction using cone beam geometry. We have developed both types of approaches one for neutron while the other for x-rays. This paper will review some of our work on 3D neutron tomography using the first approach of 3D tomography using stacks of multiple 2D scans and then using volume and surface rendering technique to visualize such data. This technique has been extensively used at APSARA reactor at Bhabha Atomic Research Centre(BARC), Mumbai for various applications.

For X-rays, we have developed a cone beam tomography setup at BARC, which has also been used extensively for various applications. We discuss on the tools and techniques used for this work and its applications in tomography of large volume objects and in micro-tomography. We also describe new trends in tomography using synchrotrons and our efforts to design phase sensitive synchrotron beamline for phase contrast tomography and microtomography.

Development of Computer Aided Tomography Systems in DRDL

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Computer Aided Tomography (CAT) development is multi disciplinary in nature involving x-ray technology, scintillation detector array, a CNC based manipulator to translate and rotate objects and a software reconstruction algorithm for image reconstruction, tomograms are slices of cross-section of objects and a 3D visualization is possible making use of multiple slices and 3D rendering software. For a fixed focal geometry, one encounters fan beams emanating from one point of source of variable focal spot sizes. If the object is placed in half power point between source and detector, good cross sectional images can be generated. In DRDL the major goals of CAT is to build a system from which large objects like 1000mm dia and 2T weight can be scanned. This is based on a six axes manipulator. In order to carry out research and development, an experimental system which can handle objects of 300 mm dia and 200 kg weight has also been built. This is based on a 4 axes manipulator. Both the systems are operational. A 256 channel detector array has been procured and used for data collection after x-ray passes over the objects. The reconstruction software is based on convolution back projection (CBP) algorithm, which has been tested and found to yield good images of cross section. This algorithm can take fan beam data and if parallel beam data is available by some means they need to be converted to fan beam data. The CBP algorithm is designed for projection data of monochromatic source. In practice, the x-rays from standard sources exhibit polychromatic spectrum. This introduces errors, which need to be corrected. This effect is known as beam hardening effect. Beam hardening can be corrected by both hardware and software filters. Hardware filters have been tested using 4 axes system whereas software algorithm developed by IIT Kanpur is under implementation at DRDL. In order to cut down the development time, we have involved multiple institutions like IISc, IIT(M), IIT(K), ANURAG, WIDIA and HMT and the total system realization has been carried out in DRDL with mostly in-house man power.

In this lecture, the details of the system developed and the experiences gained in reconstruction of Tomograms, the problem encountered in system integration and future plans will be covered.

Determination of 3-D Concentration Field around a Growing Crystal Using Laser Shadowgraphic Tomography

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Crystal growth from solution is a complex phenomenon involving double diffusive convection. The temperature and concentration fields affect the growth process in an intricate manner, particularly the growth rate, surface microstructure and hence the growth mechanism, and the defect structure of the crystal [1]. In order to study the relationship between these two fields and the growing crystal, optical technique of shadowgraphy along with the principles of computerised tomography have been used to visualize the convective plumes rising above the growing crystal and to reconstruct three dimensional concentration field respectively. Since thermal field gradients are much weaker as compared to the concentration field gradients driving the convective process, we have attempted to determine only the concentration maps above the surface of the growing crystal at varying heights. Eighteen shadowgraph images are captured equi-spaced at an angular interval of 10° between $0-180^\circ$, which constitute the experimental projection data. The images are converted to refractive index field (and hence the concentration field) by solving the governing equation of the shadowgraph process [2]. The resulting two-dimensional refractive index field constitute the projection data required for tomographic reconstruction. We use both, the convolution back projection as well as the series expansion methods for reconstruction [3] for their specific advantages, beginning with the former and refining our results further using the latter. Since implementation of the CBP algorithm requires continuous projection data between $0-180^\circ$, therefore the experimental data is suitably interpolated to obtain the data missed due to the experimental constraints. This is followed by an extrapolation procedure to obtain information of the field parameter from the region lying outside the source-detector configuration. This result in the complete projection data set required for faithful tomographic reconstruction. Advantage of using the CBP algorithm is that it is faster in convergence and provides an intelligent guess for proceeding with the iterative algorithm. In addition, the CBP technique allows us to study the effects of the data-collection geometry (number of rays per unit area) and the type of filter function [4-5]. On the other hand, the iterative algorithm when started with the solution of the CBP technique provides a more accurate value of the field parameter, and takes relatively shorter time to converge. It also facilitates a crosscheck on the correctness of the converged solution [6]. During the symposium, comparison of the 3D concentration field reconstructed using the two algorithms, and the respective merits and demerits of the two for the process under study will be discussed. The instrumentation developed for conducting the laser shadowgraphic tomography experiments will also be presented.

References:

- [1]. W. R. Wilcox, Transport phenomena in crystal growth from solution, *Prog. Cryst. Growth and Charact.*, 26 (1993) 153-194.
- [2]. Sunil Verma, K. Muralidhar and V. K. Wadhawan, Flow visualization and modeling of convection during growth of KDP crystals, *Proceedings of the 4th Asian Meeting on Ferroelectric (AMF-4)*, Dec. 2003, I. I. Sc., Bangalore, India, p. 242.
- [3]. G. T. Herman, *Image reconstruction from projections: The fundamentals of computerised tomography*, Academic Press, New York, 1980.
- [4]. P. Munshi, Error analysis of tomographic filters Part I: Theory, *NDT & E Internat.*, 25 (1992) 191-194.
- [5]. P. Munshi, M. Maisl and H. Reiter, Experimental aspects of the approximate error formula for tomographic reconstruction, *Materials Evaluation*, 55(2) (1997) 188-191.
- [6]. Debasish Mishra, *Experimental study of Rayleigh-Benard convection using interferometric tomography*, Ph.D. Thesis, IIT Kanpur, India, 1998.