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A REVIEW OF NUCLEAR NON-INTRUSIVE VISUALIZATION METHODS IN INDUSTRY: COMPUTED TOMOGRAPHY AND PARTICLE TRACKING

Ashraf H. Shehata and Mohammed S. AlJohani

Nuclear Engineering Department, Faculty of Engineering, King Abdul Aziz University
P.O. Box 80204, Jeddah 21589, Saudi Arabia, Ashehata1@kau.edu.sa and mjohani@kau.edu.sa

ABSTRACT

The present paper reviews the foundation and application of gamma-ray transmission Computed Tomography (CT) and Radioactive Particle Tracking (RPT) methods in industry. Those methods are primarily useful in oil and petrochemical industries, where processes need to be diagnosed for the purpose of design and/or operating conditions optimization.

There are two categories of industrial tomography systems; those using a single source and automatic scanning, and those using multiple sources and/or detectors without mechanical scanning. The main purpose of the latter is to reveal the multidimensional distributions of phases in industrial processes involving multiphase mixtures and flows. Compared to medical tomography temporal resolution is more important for these systems than spatial resolution. Such systems have also been realized using electronic scanning of multiple X-ray sources. Examples on different systems are given. Future developments include dual energy and multiple modality configurations enabling component fraction measurements on multiphase systems. Tomographic methods are also being implemented in permanently installed gauges with a limited number of projections, a priori information and parametric description of the process rather than reconstructed images.

Along with the CT techniques, Radioactive Particle Tracking (RPT) is another useful multiphase reactor characterization technique, where it is possible to non-intrusively monitor the Lagrangian trajectories of a single tracer particle faithfully mimicking the phase being investigated. Differentiation of particle trajectories data yields particle instantaneous velocities. Ensemble averaging yields time averaged quantities and the spatial flow field. The instantaneous and time averaged velocities can then be used to determine various turbulence parameters (Reynolds stresses, turbulent kinetic energy, and turbulent eddy diffusivities …etc.). Detailed description and application examples of RPT are given. Future developments include dual particle tracking and simpler tracking systems.

Finally, the paper gives an overview of planned research programs and service capabilities of the nuclear engineering department at King Abdul Aziz University incorporating the reviewed diagnostic tools

Keywords Computer tomography, radioactive particle tracking, multiphase flow visualization, flow characterization

1. INTRODUCTION:

In the world of industrial process, engineers are constantly facing a requirement for more information and insight to facilitate increasingly complex processes running at smaller margins. Key issues such as improved process control, process utilization and process yields, are ultimately brought forward by cost effectiveness, quality assurance, environmental and safety demands. This has accelerated the development of measurement principles including those using nuclear radiation. The application of nuclear measurement systems in industry was initially boosted by research and development in the nuclear power reactor industry where the radioisotope in many ways is a by-product. Later on those measurement systems have played an important role in the characterization, diagnosis and development of new and improved industrial processes. It is useful to categorize these measurement systems according to their mode or nature of operation:

Firstly, laboratory instrumentation where prototype process systems are built and characterized and vigorously analyzed in specialized laboratory facilities. The instruments may be characterized as complex and sophisticated yielding high performance measurements and advanced data analysis. For industrial purposes such facilities are in some cases used for periodic process samples, however, it is more often used for research and development of processes, process models and equipment.

Secondly, there is process diagnostics instrumentation, which is brought to the plant and used by specialized personnel. Data is normally recorded for subsequent off-line analysis. Typical applications are scanning of process columns and reactors, tracer investigations and non-destructive testing of equipment and structure. Radioisotope gauges have been used for this type of measurements for more than 50 years, and is still widely used. Often multiple measurements are carried out in a scan for instance by manually lowering a source down one side of a vessel and a detector down the other to build up a vertical density profile. A trained operator can then easily interpret this signature and provide information on the state of the process as well as the process vessel. This is very valuable for decision making even though it is not necessarily high-resolution measurements. The instrumentation needs to be portable and rugged, suitable for operation in rough environment. Radioisotope sources are used for the majority of these examinations. High-energy gamma-rays are used to measure differences in density, most often by transmission but also by scatter measurements on vessels with large diameter or thick walls, whereas neutron backscattering is applied where differences in hydrogen density of process components can be utilized [1]. Various logging and NDT (Non Destructive Testing) applications also fall in the process diagnostics category.

Finally, there are permanently installed gauges also known as nucleonic control systems (NCS). This instrumentation provides real-time measurements and on-line analysis, and is in some cases used for closed loop control. Here speed of response able to cope with the process dynamics is often of primary importance in comparison to what is the case with the previous categories. Sealed radioisotope sources are used for most permanently installed gauges, although there are a few examples of automatic injection tracer installations and systems using X-ray tubes and neutron generators.

In the area of multiphase reactors, two non-invasive nuclear measurement and diagnosis techniques have drawn special attention from process scientists and engineers namely, Gamma-ray Computed Tomography (CT) and Computer Automated Radioactive Particle Tracking (CARPT). While CARPT is too complicated and delicate nuclear measurement system and thus belongs to the first category described above, the CT can readily be made portable and integrated and therefore can fit in the second and even the third categories of industrial process nuclear measurements systems.

2. COMPUTER TOMOGRAPHY (CT) MEASUREMENT SCHEMES:

The foundation of all industrial nuclear measurement systems is the combination of one or several radiation sources and one or several radiation detection units, Figure 1. Important process or system parameters are then derived from the measurement of interactions between the ionizing radiation and the process or system under investigation.

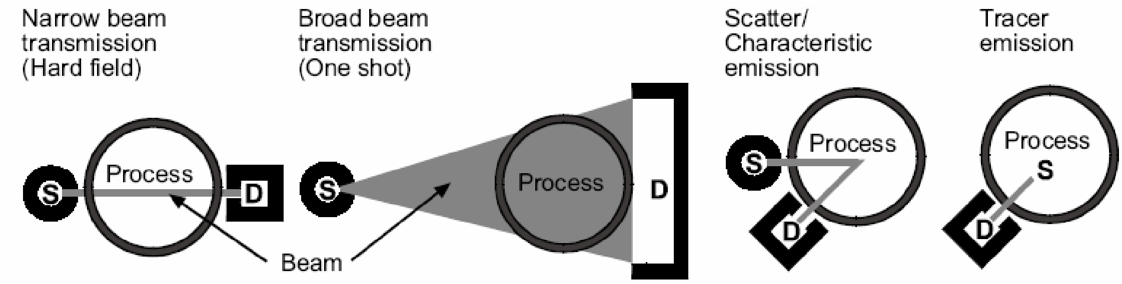


Figure 1: Measurement schemes used in industrial gauging systems.

The radiation source (S) is shielded and collimated except in the case of tracers (and NORM – Natural occurring radioactive materials) where the source is an integral part of the process. Likewise collimation and shielding are applied to the detector(s) (D).

Tomography systems are usually based on the first and second measurement schemes (Narrow beam transmission and Broad beam transmission). Tomography systems based on scatter [2] and characteristic X-ray emission [3] have been developed, however, these suffers from relatively low response intensity, particularly the latter. Radioactive Particle Tracking (RPT) by definition belongs to the last (Tracer emission) measurement scheme. Radioisotope tracing and radioactive particle tracking is a powerful tool for process diagnostic and laboratory measurements. For process diagnostics, tracer studies are frequently used for measurement of flow rate and residence time and for leakage detection [1]. Radiotracers are also the foundation of a range of advanced laboratory methods primarily used to provide experimental process data otherwise not available. These data provide improved understanding of various processes and their dynamics and are often the key for the development of accurate process models and their validation. The most widely known method is positron emission tomography (PET) [4, 5] where a short-lived β^+ emitter, such as ^{18}F, is used as the tracer isotope. PET imaging of industrial processes uses instruments developed for medical imaging. This is also true for industrial transmission tomography where the X-ray scanner has found widespread use (see e.g. [6]) since the first commercial scanner was introduced by EMI in 1972. On the other hand there have been developed a large number of dedicated tomography systems based on gamma-ray transmission, often because the relatively higher energies enables imaging of processes hidden behind thick process vessel walls.

The object's volume measured in gamma-ray transmission measurements is defined by the collimation of the source, which in most cases is a point source, and the size or collimation of the detector. A narrow source and detector collimation defines the object's volume to be measured accurately and every transmission measurement is only dependent on the process properties inside the object's volume. Therefore, there is none or only marginal contribution from scattered radiation outside that volume. In tomographic terms this is referred to as the “hard-field” property. This is satisfactory as long as the process conditions in the object's volume are representative of those of the full process cross section. In some cases this is not true and a wide collimation and large detector is used defining the so called one-shot measurement geometry [8] Figure 1. The measured intensity will now have an additional contribution from scatter, or the so called build-up. A broad beam solves the measurement problem is some cases, but not always.

For instance in multiphase systems, where the components are separated, the measurement response will be dependent on the distribution of the components. In some multiphase processes it is also necessary to know the distribution of the components inside vessels because this is of a great importance for the process performance. For instance, in some cases the components should be homogeneously mixed to promote different types of reactions, and on the contrary, in separation processes the opposite is desired. In such cases multiple narrow beam measurements or full tomographic measurements are required.

One of the major advantages of narrow beam tomography is the hard field property, which means it is possible to produce high quality images and the spatial resolution is a question of the number of detectors and their individual size. As for any other tomographic principle, there is a trade-off between speed of response (temporal resolution), and spatial resolution. The requirement for spatial resolution is normally more relaxed in industrial tomography compared to medical tomography. Spatial resolution is often sacrificed to achieve higher temporal resolution, particularly for high-speed imaging. In many cases medical and industrial tomography also differs in that in medical applications the doctor interprets the image and implements the required action. This interpretation and decision would need to be an integral part of an industrial tomography used for automatic control. In such cases there is no need for producing an image at all and a few parameters describing the process are sufficient.

3. GAMMA-RAY TRANSMISSION TOMOGRAPHY:

Gamma-ray transmission meters are one of the oldest nucleonic gauging techniques and yet are still widely used in the mining and metallurgy, pulp and paper industries, chemical and petrochemical industries, food and animal feed processing, and variety of offshore drilling fluid/mud measurement applications. When gamma-rays travel through matter they are attenuated to an extent which depends upon the density and composition of the matter, and the distance the rays travel through it. The attenuation of a narrow beam of mono-energetic gamma photons penetrating a homogeneous material follows the simple Lambert-Beer's exponential attenuation law:

$$I = I_o e^{-\mu x} \tag{1}$$

Where I_o is the initial intensity of the gamma-rays beam incident on a target material of thickness x and having a characteristic linear attenuation coefficient μ. Here I represents the remaining or un-attenuated beam intensity.

So, by selecting gamma-ray sources with correct emission energy it is possible to measure the thickness of material of constant attenuation coefficient, or the attenuation coefficient of material of constant thickness. At high gamma-ray energies (e.g. ^{137}Cs or ^{60}Co sources), where Compton scattering is the dominant interaction mechanism, the attenuation coefficient is a characteristic parameter of matter whose value strongly depends on the energy of the incident photons and the density of the attenuating matter. Therefore, gamma-ray transmission measurements can be adapted to measure the attenuation coefficients, and hence the densities, of known thickness targets. Depending on the measurement configuration, typical sensitivity of high-energy gamma-ray transmission gauges, the so called gamma-ray densitometer, is about 0.001 g/cm^3 [7]. At low energies (e.g. ^{241}Am) the attenuation coefficient depends strongly on the chemical composition (atomic number) of the attenuating material (see Figure 6). This can be utilized to provide even higher sensitivity than what is possible at high energies. Low energy meters are only used for permanently installed gauges whereas high-energy meters also may be used for clamp-on installation, for instance, in process diagnostics.

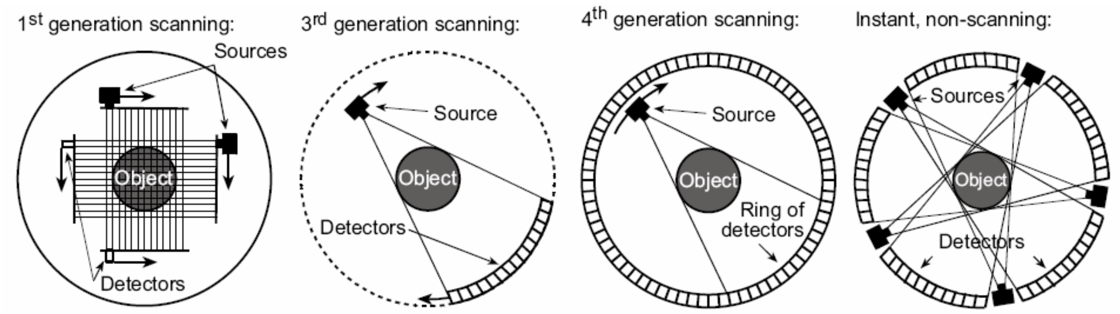


Figure 2: Measurement geometries used for medical X-ray CT scanners of 1st, 3rd and 4th generation. Also shown is the instant configuration in which all ray-sum measurements are carried out simultaneously [7].

Most gamma-ray transmission tomography systems are based on one or several fan-beam collimated point sources each facing an array of detectors on the opposite side of the process or object under investigation, Figure 2. These systems fall into two categories; those using one source and mechanical scanning to obtain multiple projections (3rd or 4th generation), and those using multiple sources and thus avoiding mechanical scanning (instant). For imaging of fairly static objects or processes, or where temporal averaging of their dynamics is satisfactory, the first is preferred because of the much lower cost. However, instant imaging has to be used on dynamic objects or processes to avoid inconsistency in the measurement cross section. Typical examples on dynamic processes with time constants in the sub second region are multiphase flows and processes involving separation, sedimentation, filtration, mixing, etc. Instant tomography is also needed for imaging of objects carried on production lines such as a conveyer belts.

4. SCANNING TRANSMISSION TOMOGRAPHY:

There are many gamma-ray tomography developments based on 3rd generation configuration in Figure 2 and temporal averaging measurements. For process diagnostics this has also been applied with only one detector acquiring data at several positions. Full data acquisition is thus obtained by scanning both source and detector. This has proved to be successful and revealed process conditions [9], which would not be detectable with one or two measurements at each level in a scan of, for example, a chemical reactor. The performance of tomography systems is experimentally evaluated using phantoms to simulate the process of interest and thus provide accurate reference conditions. The system shown in Figure 3 is designed for imaging of liquid flow distribution in trickle bed reactors, and the example uses 17 phantoms with different gas fraction. A 300 mCi ^{137}Cs source and 32 BGO scintillation detectors are used, and by scanning a maximum number of 16000 transmission measurements, so called ray-sums, are obtained. The reported gas fraction (or liquid retention) error is 3% at maximum.

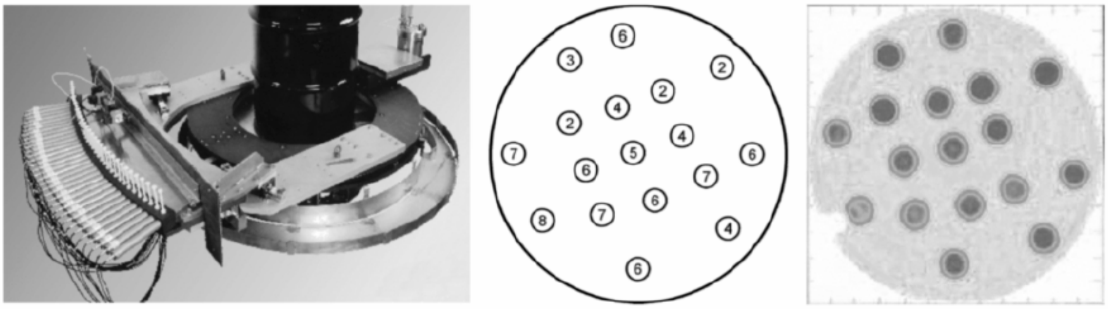
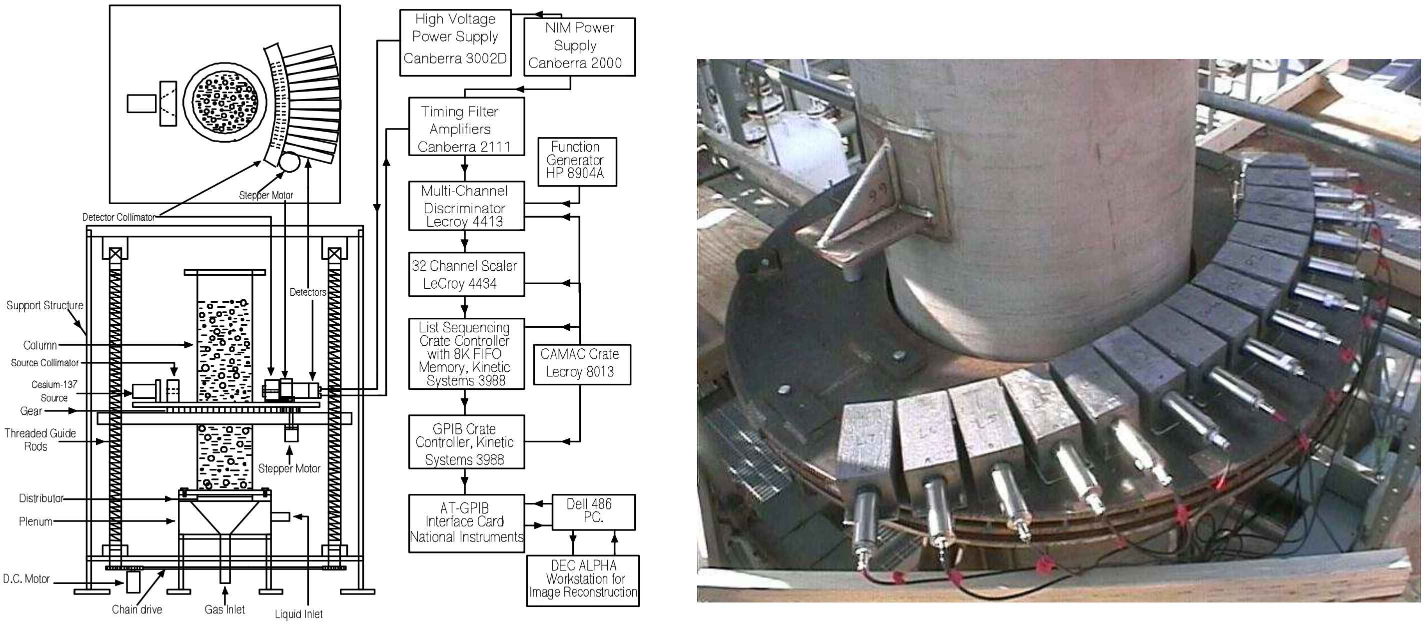


Figure 3: The 32-channel gamma-ray scanner developed with a reconstructed tomogram (rightmost) produced using 17 phantoms (flasks) each 60 mm diameter in a catalytic bed with 60 cm diameter. The gas fraction simulated by each phantom spans from 0% for phantom 1 to 100% for phantom 8. The grayscale code in the reconstructed tomogram is white and black for areas of low and high attenuation coefficient, respectively [11].

Clamp-on systems for pipeline inspection for measurements have also been designed [10]. There are also a large number of developments on systems used for process characterization and design of equipment through onsite gamma-rat computer tomography measurements [11, 12] as seen in Figure 4.



(a) (b)

Figure 4: (a) A schematic of a typical industrial process CT system, (b) A photograph of a clamp-on onsite CT scanner system, courtesy from Chemical Reaction Engineering Laboratory (CREL) at Washington University in Saint Louis.

5. HIGH SPEED TRANSMISSION TOMOGRAPHY:

Computer tomography (CT) theory implicates that objects exhibiting some symmetry and homogeneity characteristics can be reconstructed successfully from very few views [13]. This inherent property has an important potential in instant non-scanning geometry systems like the one shown in Figure 2; where a very large number of sources and detectors would make such systems very expensive. An 85 ray-sum gas/ liquid flow imaging system has been constructed [14] see Figure 5. This comprises five 500 mCi ^{241}Am sources and a total of 85 CdZnTe detectors each 1x1 cm^2. The design is for an 80 mm inner pipe diameter and the spatial resolution is about 5 mm. The temporal resolution is a few ms corresponding to an image rate of several hundred frames per second.

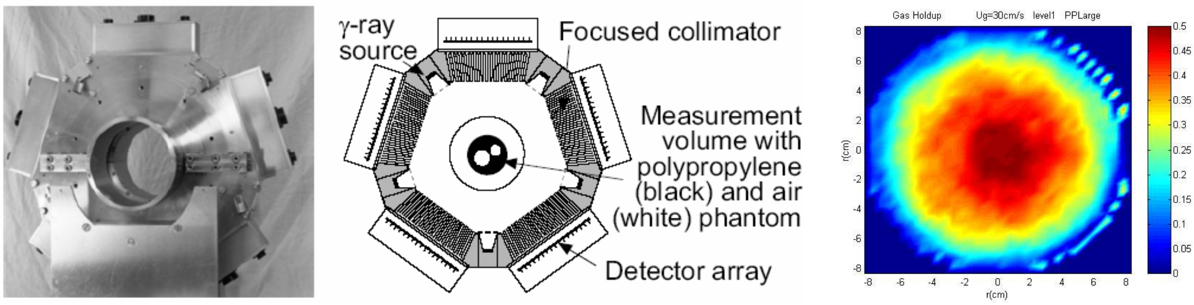


Figure 5: Reconstructed tomogram obtained with a phantom in the non-scanning 85 ray-sum gamma-ray tomography developed [14]. The integration or counting time is 10 ms.

6. DUAL ENERGY AND MULTIPLE SCHEMES METHODS:

The need for component fraction measurements in multiphase processes lead to the development of what is called dual energy meters. Here energy sensitive detectors are used and the transmission is measured at two energies. The highest energy is chosen where Compton scattering is the dominant attenuation mechanism in the mixture, Figure 6. The linear attenuation coefficients of the components are then proportional to their densities. The lowest energy is in the range dominated by photoelectric absorption where the linear attenuation coefficients are strongly dependent on the effective atomic number or composition. Thus the difference in attenuation is proportional to the density in the Compton dominant region (for absorbers with $Z/A \approx 0.5$), and proportional to Z^4 to Z^5 in the photoelectric region, where Z and A are the effective atomic number and the effective atomic weight of the composition, respectively. The result is two independent measurements enabling determination of the volumetric fractions of three components in a closed system. This principle was first developed for gas/oil/water measurements [15], and later also for ash in coal measurements [16]. The difference in dependency of photoelectric and Compton attenuation to the process density and atomic composition may also be measured by the dual modality principle using one low radiation energy (e.g. ^{241}Am sources). Here one transmission measurement responding to both photoelectric and Compton attenuation, are combined with one scatter measurement from which the Compton response is derived [17]. A dual modality system based on scatter and annihilation radiation for measurement of ash in coal has also been developed [18]. Low-energy systems require low attenuation vessel walls (or windows therein) and are often used as part of a multiple measurement system such as in conjunction with other measurement principles (e.g. electrical capacitance or conductivity) and volumetric flow measurements in multiphase flow meters [19]. Gamma-ray tomography systems using multiple schemes and/or multiple energies have been proposed, but have not yet been fully realized.

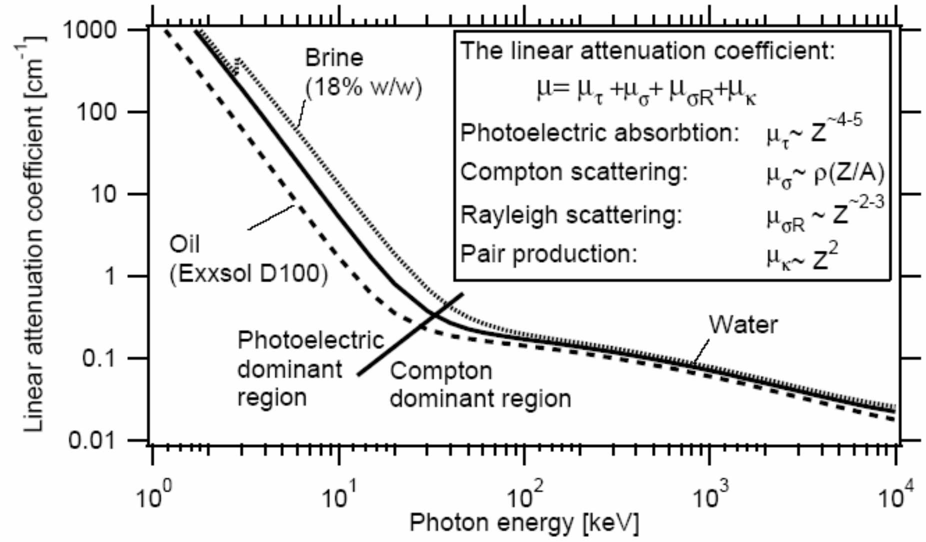


Figure 6: The linear gamma-ray attenuation coefficient of oil, water and brine.

7. RADIOACTIVE PARTICLE TRACKING:

Along with the CT technique described above, a very useful multiphase reactor characterization technique, namely, Radioactive Particle Tracking (RPT) is necessary to monitor the dynamics of a specific phase in a multiphase flow regimes represented by the Lagrangian trajectories of a single tracer particle faithfully mimicking the phase in question [22]. In this technique, the tracer particle is made dynamically similar to the phase being traced. In a Computer Aided Radioactive Particle Tracking (CARPT), a single, small (typically 90 µm – 2.3mm), composite radioactive particle (emitting gamma-ray) of density similar to the density of the tracked phase is introduced into the column to monitor liquid or liquid element motion in gas-liquid system, for example. Alternatively, a radioactive particle, identical in size and density to the solids that are traced is used to monitor solids motion in gas-solid, liquid-solid and gas-liquid-solid systems. The instantaneous particle position is identified by monitoring simultaneously the radiation intensities at a set of sodium iodide detectors (typically, 16-32) located strategically around the column. The essence of Computer Automated Radioactive Particle Tracking (CARPT) methodology is schematically presented in the Figure 7. In addition to the radiotracer and the detectors, a CAMAC (Computer Automated Measurement and Control), GPIB (General Purpose Interface Bus), and a PC complement are used to simultaneously acquire data from radiation detectors. The radiation intensity recorded at each detector decreases exponentially with increasing distance between the particle and the detector.

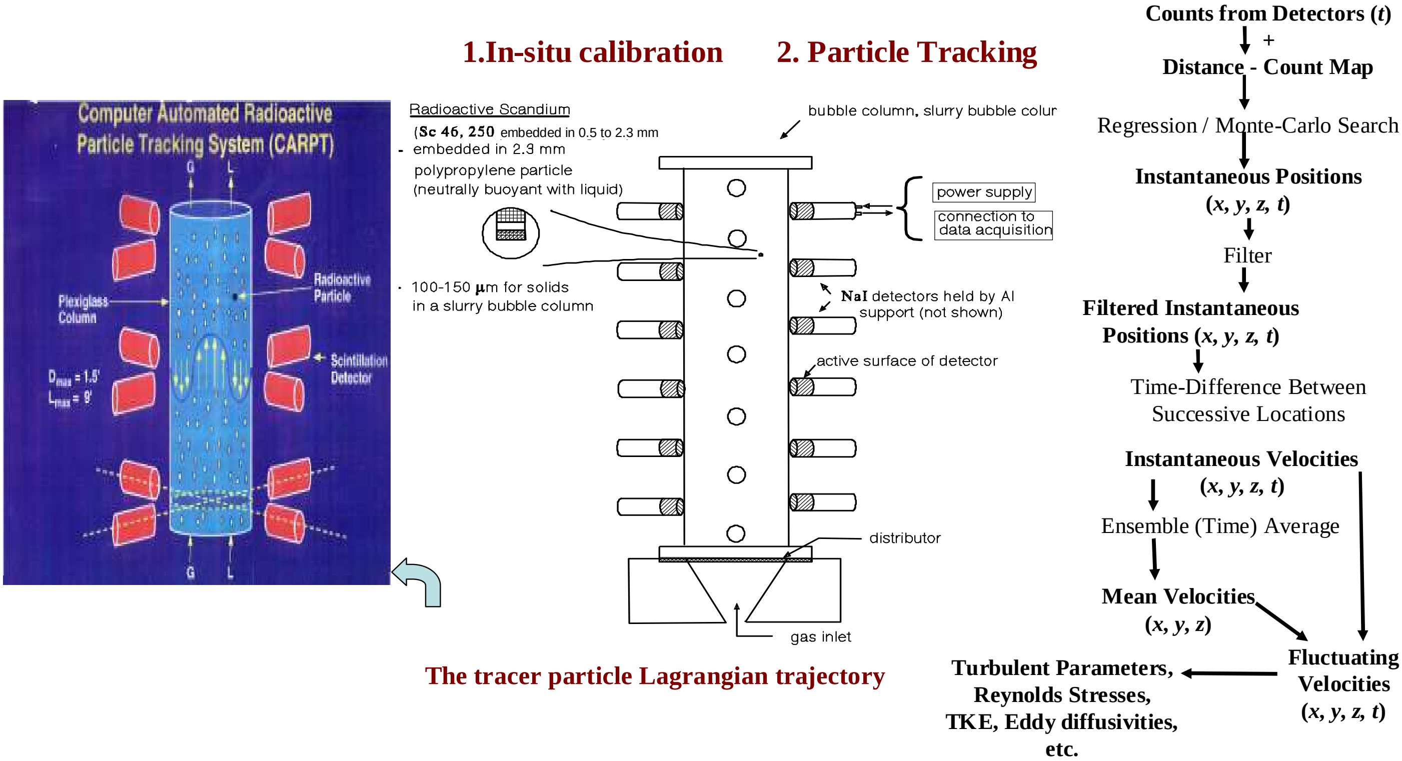


Figure 7: A schematic of a typical Computer Automated Radioactive Particle Tracking (CARPT) system.

In order to reconstruct the position of the particle from radiation intensities calibration is performed prior to a CARPT measurement by placing the particle, while the reactor is operated at the same conditions of the CARPT measurement, at various known locations and monitoring the radiation recorded by each detector. Using the information acquired, calibration curves are established that relate the intensity received at a detector to the distance between the particle and the detector. Once the distance of the particle from the set of detectors is evaluated, a weighted regression scheme is used to estimate the position of the particle at a given sampling instant in time. Thereby, a sequence of instantaneous position data is obtained that yields the position of the particle at successive sampling instants (i.e. trajectory).

Particle trajectories, at constant gas and liquid superficial velocities, are monitored and mapped out over a long period of time. Differentiation of the data yields particle's instantaneous velocities. Ensemble averaging, at various column locations, yields time averaged quantities and the spatial flow field for the whole column. The instantaneous and time averaged velocities can then be used to determine various turbulence parameters (Reynolds stresses, turbulent kinetic energy, and turbulent eddy diffusivities). Figure 8 demonstrates the Lagrangian trajectories and some of the parameters that can be obtained by CARPT measurements.

It should be noted that, CARPT is the only non-invasive technique that maps the flow field in the whole chemical reactor and provides particle Lagrangian velocities throughout the process column. It is the only technique that can accomplish this with no limitation on gas velocity or opacity.

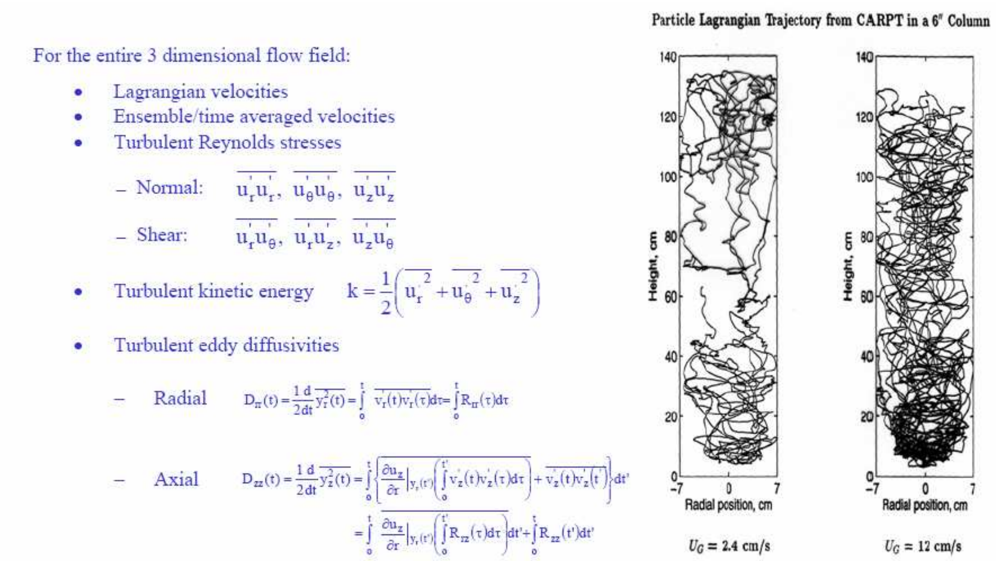


Figure 8: Some of Fluid Dynamics Quantities Directly Obtained from CARPT measurements and Lagrangian Trajectory at various Gas Superficial Velocities in a Gas-Liquid Column.

8. OVERVIEW OF PLANNED RESEARCH AT KING ABDEL AZIZ UNIVERSITY (KAAU):

The nuclear engineering department at King Abdul Aziz University is considering the initiation of extensive research programs in the field of nuclear non-invasive process visualization and monitoring techniques incorporating the described diagnostic tools.
Very few academic laboratories around the world have this CARPT-CT combination that provides the capabilities for studying systems with large volume fraction of the dispersed phase (i.e. called opaque systems). To our knowledge, there are only three academic laboratories have such capabilities, all located in the United States of America. The Chemical Reaction Engineering Laboratory (CREL) in the chemical engineering department of Washington University in Saint Louis (WUSTL) is probably the largest and most elaborate research program of worldwide reputation in reaction engineering. CREL caries out many research projects including development of benign processes, bio-fuel processing, namely ethanol production from corn, high pressure bubble/slurry bubble column, trickle-beds, packed bubble columns (non-structured and structured packing), stirred tanks, liquid-solid and gas-solid circulating systems, with special attention dedicated to photobioreactors, biodigesters, and waste water treatment processes.

In nuclear engineering department at King Abdul Aziz University, we had the privilege of initiating a contact with CREL to establish a collaboration program. CREL staff members showed great interest in continued interactions with our research group. They are willing to offer all means of technical and scientific support to our proposed research program. As CREL has already an established interaction with a number of national and world renowned university laboratories dealing with various aspects of multiphase systems (such as those at the Ohio State University, Rensselaer Polytechnique University, University of Delft, and Twente University in Holland, University of Norway at Trondheim, University of Stuttgart, University of Hannover and Dresden University in Germany, ENSIC at Nancy in France, Waterloo University, Ecole Polytechnic and Laval

University in Canada, National Technical University of Athens in Greece, Almeria University in Spain and the National Chemical Laboratory in Pune, India), we expect to further technically benefit from such wide scientific interaction and exposure. We intend to expand such interactions in the forthcoming years.

The proposed research program at KAAU is intended to establish a long tradition as a premier academic institution. The program advocates advances in multiphase reaction engineering, facilitates transfer of new findings to industrial practice and educates and trains new generations of versatile engineering experts of multi disciplinary backgrounds with strong grasp of fundamentals. The proposed research program's focus on nuclear non-invasive monitoring of multiphase systems is timeless as it addresses the basic needs of wide range of industrial processes, where an overwhelming percentage of reaction systems (over 95%) in practice are heterogeneous in nature, i.e. involve more than one phase. Quantifying of such processes performance demands understanding of both, micro-scale (single eddy, single catalyst particle scale) transport kinetic interactions, and reactor scale flow patterns and phase contacting. Such quantification leads to predictive models for process design, scale-up/scale-down, troubleshooting, and control operation.

Being an educational institution, we strive to provide a unique and stimulating environment for our students. We expect them to gain a broad knowledge of industrial processes engineering principles so that they can effectively use the state-of-the-art engineering knowledge in a variety of diverse applications. The proposed research program is sought to provide rapid transfer of academic research to industrial practice via developing and maintaining close ties with industry. We plan to serve our industrial sponsors in many ways:

1. by keeping them informed of the latest advances in reaction engineering,
2. by offering access to unique experimental facilities and the best available multiphase flow models,
3. by providing consulting services and contract work,
4. by sending qualified students to work on company premises,
5. by offering training opportunities for industrial personnel and short courses,
6. by doing joint research,
7. by allowing member companies to provide input for long-term research and for selection of future thesis projects, and
8. by providing our sponsors with the opportunity to leverage resources.

As current trends in industry are to downsize and increase the efficiency and company profit margins, this had many side effects. For example, even the largest companies cannot afford any more to have teams of scientists and engineers maintaining their expertise in general areas, they are forced to specialize. Nor can the companies afford to maintain the facilities and equipment for cold flow modeling, pilot plant scale investigations or rigorous kinetic studies. Yet, the diversity of the business that they pursue and the constant pressure to scale-up new production more rapidly, or improve existing plants; require general expertise and tools for modern scale-up. Our proposed program offers a unique opportunity to many industrial clients for leveraging their resources effectively. We can be a valuable partner for improved troubleshooting of existing processes and in scale-up of new ones. We can also offer breadth and depth in the general methodology of reaction engineering via some unique facilities. In this new business climate, association with our proposed program would become an even more valuable asset to our industrial partners.

9. CONCLUSIONS

The combination of Computer Automated Radioactive Particle Tracking (CARPT) and Computer Tomography (CT) provides a wealth of crucial engineering information needed for either process design and optimization, or diagnosis and troubleshooting. Such information include but not limited to, measurement of instantaneous velocities, turbulence and back-mixing parameters, time averaged circulation patterns and complete voidage (holdup) distribution in multiphase gas-liquid-solid, gas-liquid, liquid-solid and gas-solid systems such as bubble columns, fluidized beds, risers and stirred tanks.

In addition to the importance of the radiotracers applications in the petrochemical industries using the mentioned techniques of CT and RPT, there is a continuous need to perform extensive research to improve and develop the techniques themselves. The need for such research arises from the fact that there is always a possibility and need to enhance the accuracy and credibility of the results obtained via those techniques, in terms of increasing spatial resolution, time resolution, and extension of the techniques utilization to real time applications. We are quite aware and certain of many innovative research ideas that are directly linked to the research and development needs mentioned above.

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