Radiotracer Applications in Industry

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Abstract

Radiotracers are widely used for troubleshooting, measurement of hydrodynamic parameters, characterization of mixing and flow visualization in industrial process systems. The commonly carried out industrial applications include leak and blockage detection in buried pipelines and heat exchangers; measurement of residence time distribution, flow rates and mixing times in industrial process systems; wear and corrosion rate measurements in metal components; tracing of fluids in oil fields and measurement of ground water velocity. In addition to this, single radioactive particle tracking technique is also used for flow visualization in laboratory or pilot-scale industrial systems and validation of the computational fluid dynamic models. Isotope and Radiation Application Division of Bhabha Atomic Research Centre, Mumbai alone has carried out a large number of radiotracer investigations during the last five decades leading to significant revenue savings to the Indian industry. Some of the important radiotracer investigations are briefly discussed in this article.

Keywords: *Radiotracer, flow rate, leak, blockage, residence time distribution, mixing time, effluent dispersion, sediment transport, wear rate, radioactive particle tracking technique*

1. Introduction

Application of radioisotopes and radiation technology in agriculture, healthcare and industry is an important programme of Bhabha Atomic Research Centre (BARC), Mumbai leading to significant societal benefits. The production of radioisotopes in India began soon after 1 MW APSARA reactor became operational in 1956. The radioisotope production capability was enhanced with the commissioning of a 40 MW CIRUS reactor in 1960 and establishment of the highly equipped radioisotope processing laboratories at Trombay, Mumbai. In addition to this, the production of mega curies activity of cobalt-60 also began in power reactors in nineteen seventies. These developments made India self-sufficient in production of radioisotopes for various applications. Subsequently, in 1985, the production capability received a major boost with the commissioning of a high flux 100 MW DHRUVA reactor enabling the availability of various radioisotopes with high specific activity in large quantities. With this, BARC started developing and using radioisotope techniques in various areas of science and technology.

In 2010, the CIRUS reactor was decommissioned after its successful operation of 50 years. Subsequently, in 2018, the APSARA reactor was upgraded with capacity from 1 MW to 2 MW and was renamed as APSARA-U. At present, DHRUVA and APSARA-U reactors are operational at BARC, Trombay, Mumbai and used for production of more than 100 different radioisotopes for application in healthcare, agriculture and industry. In year 1989, the Department of Atomic Energy (DAE) established an independent unit named as Board of Radiation and Isotope Technology (BRIT) to cater the needs of various users of radioisotopes and radiation technology in the country. The BRIT Mumbai supplies radioisotopes and radiation equipment to the various users in India and abroad, and along with the BARC, Mumbai offers commercial services to meet the country's demand in various fields of applications. The R&D programmes for advanced applications of radioisotopes are pursued at BARC, Trombay, Mumbai.

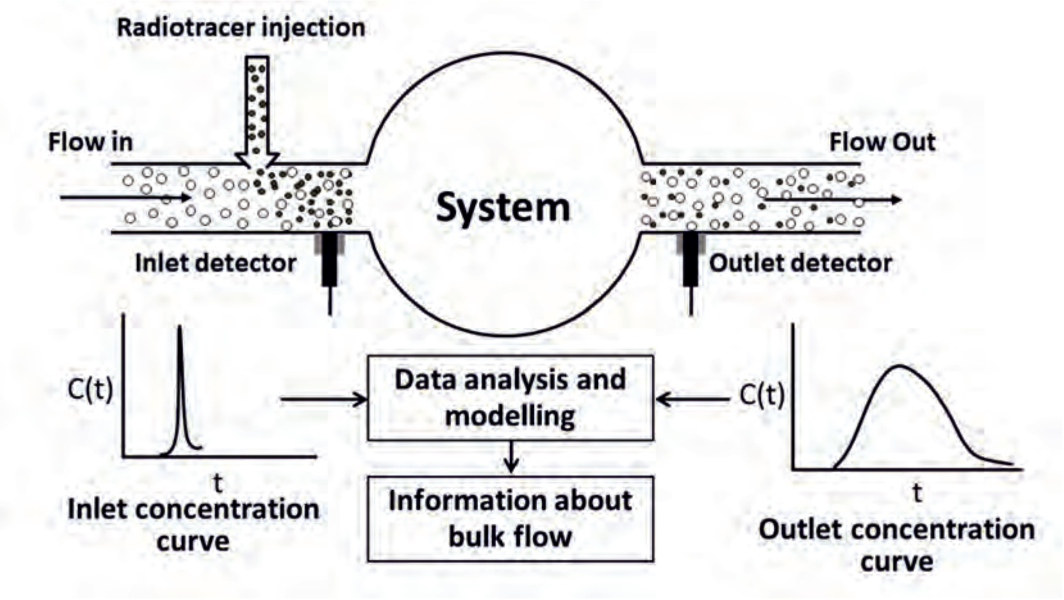

Figure 1: Principle of radiotracer technique

The radioisotope in industry are used in two different forms i.e. sealed source and radiotracer. In sealed-source applications, the radioactive material is sealed in a metal container and the emitted gamma-radiations are utilized for various applications. However, in radiotracer applications, a radioactive material in suitable form (liquid, solid and gas) is introduced into the feed of an industrial system and its concentration is monitored as a function of time at the inlet and outlet using radiation detectors as shown in Fig. 1. Subsequently, the monitored radiotracer concentration curves are analyzed to draw the information about the flow in the system. The application of radiotracers is preferred in industrial systems over conventional tracers because of their many advantages such as high detection sensitivity, feasibility of online detection, availability in wide range and ability to be used in hostile environment [1, 2, 3]. Some of the commonly used radiotracers in industry are given in Table 1. This article discusses some of the commonly carried out radiotracer applications in industry and sealed sources applications such as radiometry (scanning), radiography, tomography, nucleonic control systems and radiation processing are discussed elsewhere in this book.

Table 1: Generally used radioisotope as tracers in industrial systems

Isotope	Half-life	Radiation and energy (MeV)	Chemical form	Tracing of phase
Tritium (^{3}H)	12.6 y	β: 0.018 (100%)	Tritiated water	Aqueous
Carbon-14 (^{14}C)	5730 y	β: 0.156 (100%)	Ammonium thiocyanate	Aqueous
Sodium-24 (^{24}Na)	15 h	γ: 1.37 (100%) 2.75 (100%)	Sodium carbonate	Aqueous
Bromine-82 (^{82}Br)	36 h	γ: 0.55 (70%) 1.32 (27%)	Ammonium bromide, p-dibromobenzene, dibrobiphenyl, methyl bromide	Aqueous Organic Organic Gas
Lanthanum-140 (^{140}La)	40 h	γ : 1.16 (95%) 0.92 (10%) 0.82(27%) 2.54 (4%)	Lanthanum chloride	Solid (Absorbed)
Gold-198 (^{198}Au)	2.7 d	γ: 0.41 (99%)	Chloroauric acid	Solid (Absorbed)
Iodine-131 (^{131}I)	8.04 d	γ : 0.36 (80%) 0.64 (9%)	Sodium iodide, Iodobenzene	Aqueous Organic
Molybdenum-99 (^{99}Mo)	67 h	γ : 0.18 (4.5%) 0.74 (10%) 0.78 (4%)	Sodium molybdate	Aqueous
Technetium-99m (^{99m}Tc)	6 h	γ : 0.14 (90%)	Sodium pertechnetate	Aqueous
Scandium-46 (^{46}Sc)	84 d	γ : 0.89 (100%) 1.12 (100%)	Scandium oxide	Solid (Particles)
Krypton-85 (^{85}Kr)	10.6 y	γ : 0.51 (0.7%)	Krypton	Gas
Krypton-79 (^{79}Kr)	35 h	γ : 0.51 (15%)	Krypton	Gas
Argon-41 (^{41}Ar)	110 min	γ : 1.29 (99%)	Argon	Gas

2. Radiotracer Applications

2.1 Blockage detection in buried pipelines

The influx of the undesired materials during commissioning/refurbishment or occurrence of scaling on walls lead to blockages in buried pipelines during their operation. Consequently, the flow of the material in pipelines is hindered. The location(s) of blockage(s) need to be identified and fixed at the earliest for efficient operation of the pipelines. For removing the foreign material and scaling on the inner walls of a pipeline, usually a scrapper pipeline instrumentation gauge (PIG) is pushed into the pipeline by applying pneumatic or hydraulic pressure. The cleaning "PIG" scraps the scaling on the wall and pushes it out of the pipeline at the other end along with the foreign material, if any. Subsequently the "PIG" is retrieved and cleaned. The operation is often called as pigging operation. But often it happens that the "PIG" itself gets struck inside the pipeline due to obstruction or blockage or excessive scaling on wall of the pipeline during the cleaning operation. Thus it becomes imperative to identify the location of blockage and retrieve the "PIG".

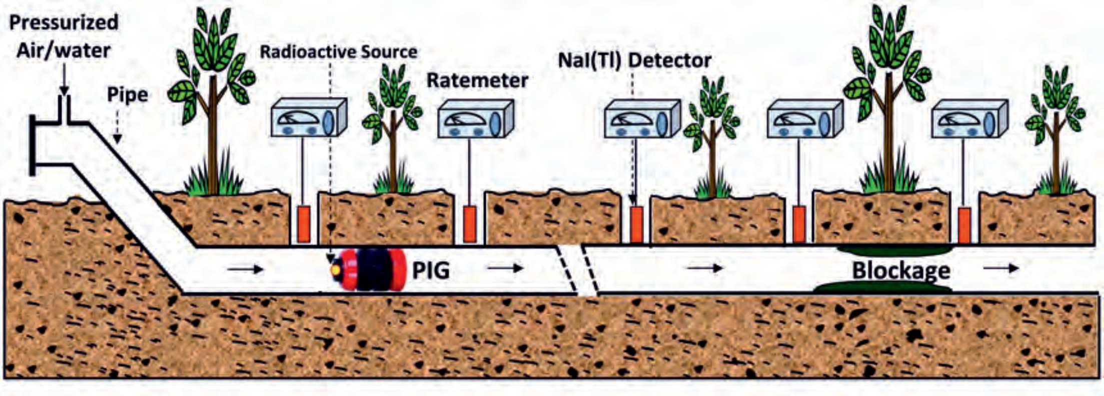

Figure 2: Principle of blockage detection in buried pipelines using radioisotope technique

Radioisotopes in the form of a sealed source are used to track the movement of scrapper "PIG" during cleaning operation of the buried pipelines in refineries, chemical and petrochemical industries. Figure 2 shows a schematic illustration of the blockage detection in buried pipelines using radioisotope technique. A sealed radioisotope source is mounted inside a cavity on the "PIG" prior to its launching. It is ensured that the cavity is properly capped so that there is no possibility of source being lost during the pigging operation. A sealed source used in pigging operations is either cobalt-60, ^{60}Co (half-life: 5.2 years, gamma energies: 1.33 MeV (100%) and 1.17 MeV (100%)) or iridium-192, ^{192}Ir (half-life: 74 days, gamma energies: 0.110-1.378 MeV) or cesium-137, ^{137}Cs (half-life: 30 year; gamma energy: 0.66 MeV (94.6%)). The activity of the source varies from 37-370 MBq. The "PIG" movement is monitored at dug trenches along the pipeline using NaI(Tl) detector connected to a ratemeter-scaler. If the detector positioned at any particular trench does not record radiation counts and sounds an alarm, it indicates blockage of "PIG" at an upstream location. The procedure can be repeated to narrow down the length of the section having the blockage. Subsequently, the soil cover is removed and exact location of the blockage is identified. The portion of the pipe having blockage is cut, replaced with the new pipe and the "PIG" is retrieved. The procedure is again repeated to identify the additional blockages in the pipeline. The technique is routinely used in India for blockage detection in buried pipelines in chemical, petroleum, petro-chemical and oil-gas industries and helps to avoid huge expenditure required to unearth the entire pipeline [4, 5]. Similar procedure is adopted for identifying the interfaces between the different fluids being transported in the same pipeline using a "PIG" made of rubber and loaded with a cobalt-60 source.

2.2 Leak detection in buried pipelines and heat exchangers

A leak in any system is defined as an undesirable interconnection between its two isolated parts and sub systems. Occurrence of leakage is a common problem in industrial systems (heat exchangers, condensers and buried pipelines) causing contamination of the product, reduction in process efficiency and pressure drop. Therefore, the timely identification and confirmation of leak(s) is essential to avoid deterioration of product quality, reduction in process efficiency, and associated safety and environmental hazards. The radiotracer techniques are commonly used for detecting leaks in industrial systems due to their above-mentioned advantages over conventional tracers [6]. The methodology for leak detection in buried pipelines depends upon the situation and varies case to case basis. Locating the actual position of the leak requires specially designed monitoring procedure depending upon the situation. There are three radiotracer methods i.e. detector pig method, velocity drop method and tracer patch migration method commonly used for leak detection in buried pipelines [1, 2]. A typical case study using tracer patch migration method is discussed below in details.

A petro-chemical industry in India had laid and commissioned a buried pipeline (length: 74 km, diameter: 15 cm) for carrying ethylene gas from a cracking plant to its premises. During the pre-commissioning testing, significant loss of pressure was observed in an 11 km long section of the pipeline suggesting occurrence of leak(s). Therefore, it was necessary to locate the leak(s) before commissioning the pipeline. The radiotracer patch migration method was used to locate the leak(s) [7]. The principle of the method and the schematic layout of the leaking section of the pipeline are shown in Fig. 3a and 3b, respectively. Two leak detection tests were carried out using ^{82}Br as methyl bromide gas as a radiotracer. In first test, about 0.7 GBq of ^{82}Br radioactive gas was instantaneously introduced into the pipeline at the factory end and its movement was monitored using radiation detectors positioned at different trenches located at an interval of 1 km along the pipeline. The radiotracer was not detected at trench No.9 (located about 10 km from the premises of the industry) and beyond suggesting occurrence of leak(s) between trench No.8 and No.9 (Fig. 3b). Therefore, the length of the leaking section of the pipeline was reduced to be 1.8 km from 11 km. Subsequently, the exact location of the leak was identified at a distance of 0.5 km away from the trench No. 8 by monitoring the leaked radiotracer gas along the 1.8 km long section of the pipeline. At the identified location, the soil cover (~1.5 m) above the pipeline was excavated and a leak of 15 mm size was visually confirmed. The leaking segment of the pipeline was replaced and pressure-testing was performed. It was observed that the pressure was still dropping but at a lesser rate indicating presence of another leak of smaller size in the 11 km long section of the pipeline. Therefore, second tracer test was carried out by injecting radiotracer gas (1.9 GBq) near SV-6 location. The monitoring of the radiotracer confirmed occurrence of another leak between trench No. 5 and trench No. 6 at a distance of about 4 km away from the factory end. The leak was found to be of 8 mm size. After the remedial measures, the pressure-testing was performed and the entire 11 km long section of the pipeline was found to be holding the necessary pressure. This indicated absence of any leakage in the pipeline and was commissioned for desired operations.

Heat exchanger systems, as shown in Fig. 4a, are extensively used in process industry and involve the counter-current flow of two fluids through two independent parts / sub-systems. The methodology of leak detection in heat exchangers in industry using radiotracer technique is illustrated in the following example. A heat exchanger system operating in a petroleum refinery

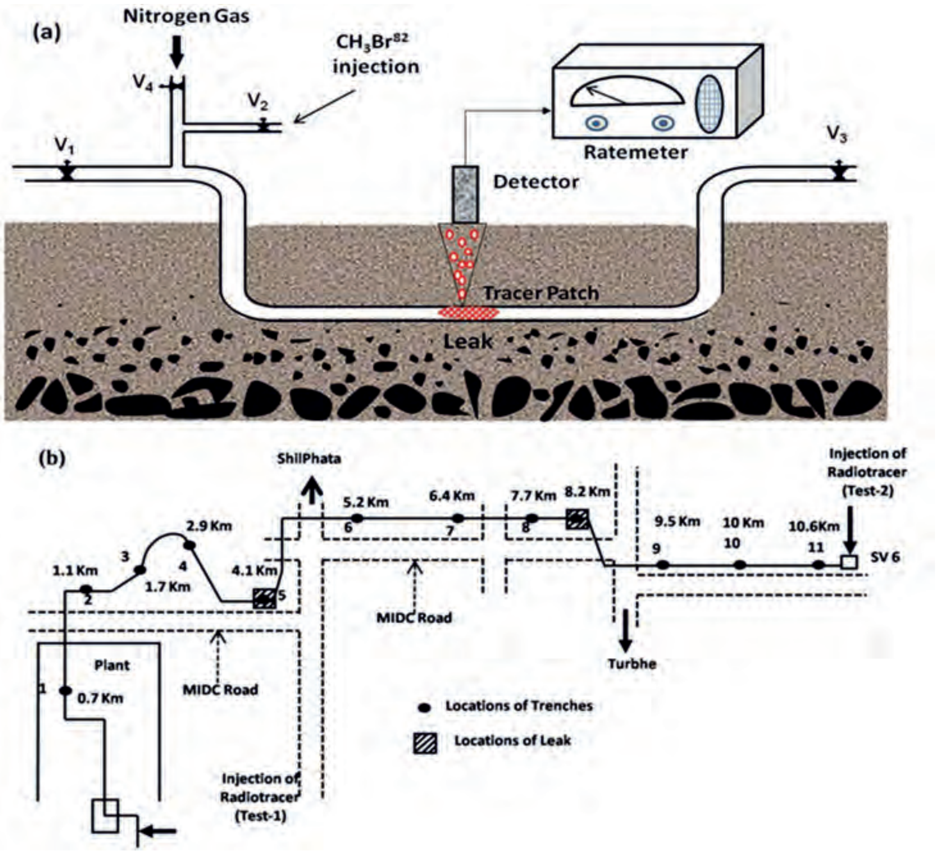

Figure 3: (a) Principle of radiotracer method to identify leak in buried pipeline, (b) Application of radiotracer patch method to identify leak in a gas pipeline

was suspected to be leaking because of more than the permissible level of sulphur content in the product stream. The schematic diagram of the system is shown in Fig. 4b. The system consisted of six independent shell-tube type heat exchangers connected in series. The feed and the effluent flowed counter-currently through the shell-side and tube-side, respectively. The shell-side was at a higher pressure than the tube side. So if there is any leakage in the system, the feed from the shell-side (higher pressure side) will leak into the product stream flowing counter-currently through the tube-side (lower pressure side). Therefore, in order to confirm the suspicion and identify the leaking exchanger(s), a radiotracer test was conducted by injecting a suitable radiotracer (^{82}Br as dibromobiphenyl) into the shell-side and monitoring its presence in the tube-side (Fig. 4b). Care was taken to inject sufficient quantity of the radiotracer so that even the lowest leak rate could be detected. Based on the monitored radiotracer concentration curves, two heat exchangers (E-2A and E-2B) were confirmed to be leaking. The leak rate in the two exchangers was estimated to be about 0.2 - 0.3 % of the feed rate. Based on the results of the radiotracer test, decision was taken by the plant engineer to shutdown the plant for remedial measures. The leaks in the two heat exchangers were visually confirmed during the shutdown. The timely confirmation and identification of the leaking heat exchangers reduced the shutdown time of the plant by about 15 days leading to significant revenue savings to the refinery [8, 9].

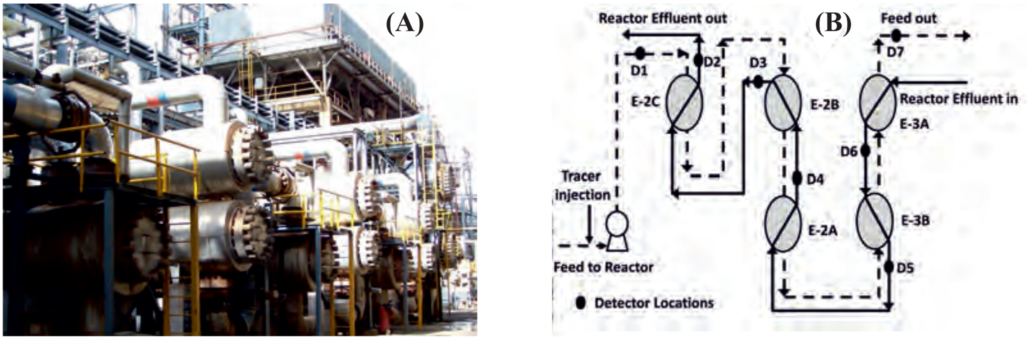

Figure 4: (a) Photograph of a typical shell-tube type heat exchanger system (b) Schematic diagram of heat exchanger system and experimental setup [8]

2.3 Flow rate measurement

Maintaining the optimized fluid flow rates in industrial systems is crucial to achieve the desired process efficiency and product quality. There are several conventional methods available for the measurement of flow rates in pipelines, canals and rivers [10, 13]. However, these methods do not provide accurate results in many situations, particularly in large industrial systems. Radiotracer techniques enable accurate measurements in such situations. The pulse velocity and dilution methods are the two commonly used radiotracer methods for flow rate measurements in industrial systems [1, 2]. A typical case study describing the application of radiotracer dilution method is briefly discussed below.

A power industry in Southern India operated a coal based thermal power plant of 1040 MW capacity located on the coast of the Bay of Bengal [10]. The plant consisted of two identical units and each of them drew the seawater for cooling through pipelines of 3.6 meter diameter. Two independent pumping stations, each consisting of two identical Vertical Turbine (VT) pumps, were used for pumping the seawater for the cooling. The cooling water after condensation was pumped back into the sea. The photograph of a section of the pipelines and the schematic layout of the cooling water circulation system is shown in Fig. 5. The accurate measurement of the flow rates was essential for water-budgeting and optimized operation of the plant. Ultrasonic flow meters were used for the measurement of flow rates of the pumped seawater in the plant. But a large variation was observed in the measured flow rates, which could have been either due to malfunctioning of the installed flow meters or the VT pumps. Therefore, it was desired to measure the flow rates in the pipelines at different operating conditions. Since the conventional tracer techniques could not be applied, radiotracer dilution method was used for the measurement of the flow rates in the pipelines [10]. ^{131}I as NaI aqueous solution was used as a radiotracer. The radiotracer solution of a known concentration (C_1) was continuously injected into the feed line at a constant rate (Q_1) for a pre-defined time period (Fig. 5). After ensuring the homogeneous mixing of radiotracer across the cross-section of the pipeline, water samples were collected from a downstream location at the plant end and radiotracer concentration (C_2) was measured. Following radiotracer balance equation was used to calculate the flow rate (Q_2) of the cooling water in the pipeline [1, 2]:

$$Q_2 = Q_1 \cdot (C_1/C_2) \tag{1}$$

The measured flow rates ranged from 14.1 - 15.4 m^3/s when a single VT pump was operated in each unit. Whereas the measured flow rates ranged from 24.55 - 27.5 m^3/s when two VT pumps were used for pumping the seawater in each unit. The uncertainty in the measured values was estimated to be about 3%. The measured values of flow rates were found to be in good agreement with the theoretically estimated pumping capacity (15 m^3/s) of the pumps. The results were used to validate the pumping capacity of the pumps, calibration of the installed flow meters, water-budgeting and efficient operation of the plant leading to significant revenue savings to the industry.

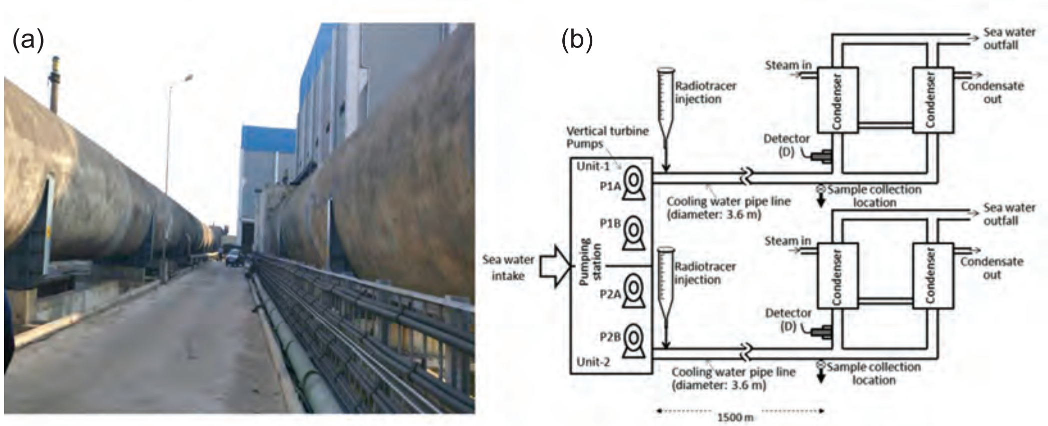

Figure 5: (a) Photograph of the pipeline and (b) Schematic diagram of the water circulation system and experimental setup for flow rate measurement [10].

2.4 Mixing or homogenization time measurement

Mixing or homogenization of two or more than two feed components is a process carried out in batch and continuous type process systems. The mixing or homogenization is often required to be measured to optimize the power requirement and evaluate the quality of the product. The radiotracer method for measurement of the mixing time involves labeling of a specific component of the feed with a suitable radiotracer, instantaneously injecting the same into the system, withdrawing the samples of the process material at a regular interval of time and monitoring the radiotracer concentration in the withdrawn samples. Subsequently, the monitored concentration is plotted as a function of time and mixing time is estimated when the radiotracer concentration becomes constant in the samples [1, 2]. Alternatively, the radiotracer concentration within the system can also be measured online by mounting the radiation detectors at different locations in the plant. A typical case study on measurement of the mixing time using the radiotracer method is briefly discussed in the following example [11].

The quality of the glass sheets produced in one of the glass industry in India was found to be poor and not meeting the product specifications. The produced glass sheets were meant for use in solar panels. The quality of the produced glass sheets depends on mixing or homogenization of molten glass within the glass furnace and associated sub-systems connected in series. Therefore, it was required to evaluate the homogeneity of the produced glass sheets and estimate the mixing time. A radiotracer method was applied as it was not feasible to use any of the available conventional methods because of high temperature (~1400 °C) and harsh conditions involved in the glass production process. The furnace and produced glass sheets are shown in Fig. 6. In the present study, ^{140}La as La_2O_3 mixed with silica powder was instantaneously injected into the feed to the furnace and produced glass sheets were collected at regular intervals for measurement of radiotracer concentration. The concentration was measured at nine equidistant locations in the sheets of 1 m x 1 m size. On plotting the measured radiotracer concentration with time, the mixing (homogenization) time of the molten glass was estimated to be 29 hours. The results of the study helped to optimize the process and improve the design of the glass production unit.

Figure 6: (a) Photograph of a furnace and (b) Produced glass sheets

2.5 Residence time distribution measurement

Residence time is the time spent by a fluid element in a process system. In an ideal system, the residence time of all the fluid elements entering the system at a particular time is the same. But in real systems the residence time of different fluid elements is different. The distribution in their residence times is defined as residence time distribution (RTD) and is a characteristic parameter of continuous flow system. Measurement and analysis of residence time distribution (RTD) of process material in continuously operating systems is often used for troubleshooting, quantification of flow parameters and characterization/visualization of flow. The approach is also used for evaluation or validation of design of pilot-scale systems at design stage itself and validation of computational fluid dynamic (CFD) models. The general methodology of RTD measurement using radiotracer is shown in Fig. 1. The methodology involves instantaneous injection of a suitable radiotracer into the feed at the inlet and monitoring its movement at the outlet or strategically selected locations along the system [1, 2, 3]. The lead collimated NaI(Tl) scintillation detectors connected to a computer-controlled data acquisition system (DAS) are used for monitoring the radiotracer concentration at a regular interval of time. The measured curves are treated and analyzed to determine hydrodynamic parameters and draw the information about the bulk flow. A large number of radiotracer investigations have been carried out for RTD measurements in Indian industry during last three decades. A representative case study is briefly discussed below.

A soaker drum or visbreaker, used for processing of heavy hydrocarbons in a petroleum refinery in India was found to be malfunctioning. The visbreaker was primarily designed to produce liquid hydrocarbon (diesel). However, the visbreaker produced large quantity of undesired gaseous hydrocarbons hindering the upstream operation of the plant. Therefore, the RTD of the process fluid was measured using radiotracer technique with an objective to characterize and visualize the flow of the process within the visbreaker [12]. The photograph of the visbreaker and the schematic diagram of the experimental setup for the RTD measurement are shown in Fig. 7. A series of RTD measurements were carried out using ^{82}Br as paradibromobenzene as a radiotracer. The radiotracer was injected as an impulse at the inlet and its concentration was measured at both inlet and outlet of the soaker (Fig. 7b). Two independent NaI(Tl) detectors coupled to a data acquisition system were used for monitoring the radiotracer concentration at the inlet and the outlet of the soaker. The measured RTDs were treated and modeled using a suitable mathematical model and flow within the soaker was visualized [12]. The results of the analysis showed the existence of two parallel flow streams i.e. bypass and well-mixed flow streams within the soaker. The distribution of flow between bypass and well-mixed streams was estimated to be 36% and 64% respectively. The existence of the undesired parallel flow streams within the soaker caused the over cracking of the process fluid resulting in more production of gaseous hydrocarbons as compared to liquid hydrocarbon. Based on the results of the RTD study, the design of the soaker was modified by inserting the suitable baffles at different longitudinal locations within the soaker. The replacement of the existing soaker with the modified soaker solved the problem of over production of gaseous hydrocarbons in the soaker plant.

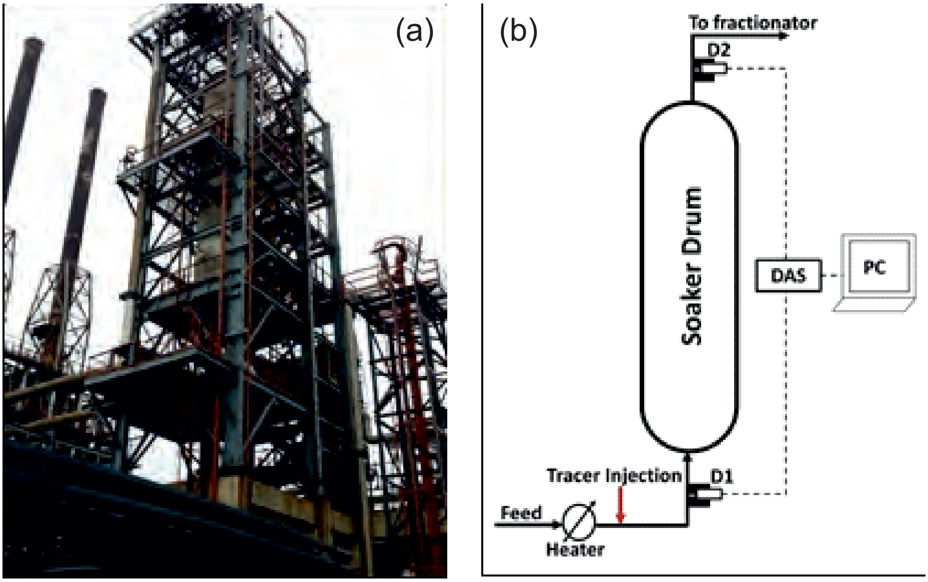

Figure 7: (a) Photograph of the soaker (b) RTD measurements in the soaker.

2.6 Sediment transport

Sedimentation of shipping channels obstructs the free movements of ships in ports. In order to maintain a desired depth (12-15 m) of water in the shipping channels, the sediments are dredged and dumped at a suitably selected location in the sea. The selected dumping site should be such that the dumped sediments are not recycled back to the channel. Moreover, the selected site should not be too far from the dredging location so that the turn-around time of the dredgers is minimized. Therefore, the knowledge of dispersion of sediments on sea bed and transport parameters is required to evaluate the suitability of the dumping sites and optimize the dumping operations. The radiotracer technique is often used for investigation of sediments on sea bed and evaluation of the dumping sites [13, 14]. Several large-scale radiotracer investigations have been carried out in all the major ports of India during last five decades. A typical case study is briefly discussed below.

Figure 8: Injection of radiotracer for sediment transport

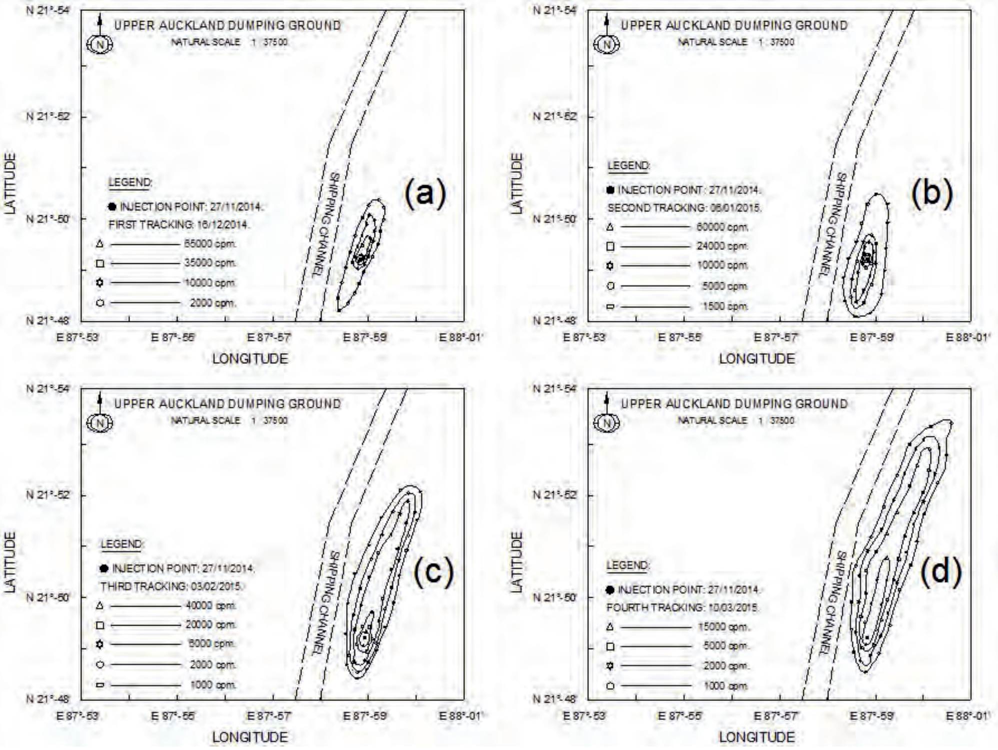

Figure 9: Isocount contours of radiotracer investigation at Kolkata Port, Kolkata [15].

At the request of Kolkata Port Trust, Kolkata a radiotracer investigation was carried out to investigate the dispersion pattern of sediments in Hooghly estuary and evaluate the suitability of a proposed dumping site [15].

Scandium-46 as scandium glass powder having similar physical properties (density: 2.67 gm/cm^3, particle size distribution: 70-100 microns) as that of the native sand was used as a radiotracer for tracing the sand on the sea bed. The radiotracer (activity: 150 GBq, mass: 200 gm) was mixed in about 4 kg of the native sand and injected at the proposed dumping site using a specially designed injection system as shown in Fig. 8. Subsequently, the radiotracer was allowed to disperse on the sea bed and its movement was tracked using a waterproof scintillation detector mounted on a sledge and connected to a ratemeter-scaler. The sledge mounted with the detector was dragged on the sea bed using a boat and the radiation intensity was recorded at discrete locations as a function of latitudes and longitudes at different time intervals. The recorded data was plotted on a graphical chart of the site and isocount contours were drawn as shown in Fig. 9. It was observed that the general direction of the movement of sediments was towards the north-east direction, parallel to the navigation channel during all the four tracking. The maximum extent of dispersion towards transverse and longitudinal directions was about 2000 m and 8000 m, respectively. The spread of radiotracer over a period of 115 days indicated that the dumped sediments moved parallel to the channel and did not find its way into the channel. Therefore the proposed site was found suitable for dumping the dredged sediments. In addition to the above qualitative information, the transport parameters such as velocity, thickness of the moving bed and sediment transport rates were also estimated [15]. The results of the study were utilized to optimize the dredging operation leading to significant revenue savings to the port.

2.7 Effluent dispersion

The industrial effluents and sewage generated in metropolitan cities are generally discharged into the nearby water bodies such as lakes, rivers, creeks and sea with or without treatment. The discharged effluents may contain toxic chemicals and pathogens and may pollute the water bodies. The tidal currents, winds as well as salinity and temperature gradients in water bodies influence the dispersion and dilution of discharged effluents. Therefore, it is necessary to investigate the dispersion of discharged effluents/sewage by demarcating the contaminated area and estimate the dilution factors. In addition to this, it is often required to understand the sewage dispersion processes for a proposed outfall or to evaluate the functioning of an existing outfall system under different tidal conditions.

A series of radiotracer studies were carried out along the Mumbai Coast to investigate the dispersion of the discharged sewage and evaluate the performance of the existing outfalls or to design new outfalls [16]. Bromine-82 as ammonium bromide, representing the discharged liquid effluent, was used in all the studies. The radiotracer was remotely transferred into a container having a large volume of sewage (~100 liters), mixed well and continuously released into the effluent channel leading to the outfall for a predetermined time period using a peristaltic pump. Subsequently, the spatial and temporal dispersion of the radiotracer in the water body was monitored using waterproof scintillation detectors deployed from boats. Subsequently, the measured radiotracer data was plotted on a graphical chart of the site and isocount contours were plotted. A typical plot of the isocount contours monitored in one of the studies is shown in Fig. 10. From the isocount contours, the maximum longitudinal and lateral spread of sewage was assessed and the area of contamination was demarcated. The dilution factors were also calculated from the ratio of radiotracer concentration (counts per unit time) at the discharge point of the outfall to the measured concentration at a particular location. Further, the measured data was modeled using a suitable analytical or numerical model and the dispersion coefficients were estimated by matching the model calculated radiotracer concentration with the measured data. Such studies were carried out at several sewage discharge locations along the Mumbai coast. The studies helped the municipal authorities to plan, manage and optimize the sewage/effluent disposal strategy.

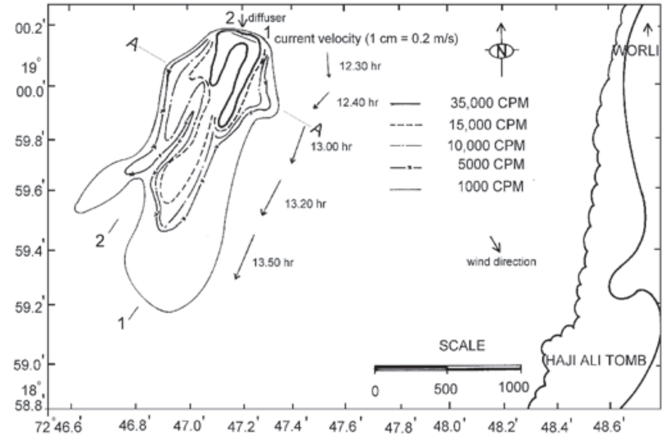

Figure 10: Isocount contours measured in an effluent dispersion investigation [16]

2.8 Radiotracer applications in oil fields

Gas and oil industry was one of the first industries to recognize the potential of radiotracer techniques and successfully used them in exploration, drilling, completion, stimulation and enhanced oil recovery (EOR) operations [17, 18]. Naturally occurring radioisotopes such as radon-222, ^{222}Rn (half-life:3.8 days, gamma Energy: 0.465 Mev (4.24%)) and its decay product have been used as radiotracers for identifying the leakage of gas from oil reservoirs during exploration stage. Typical applications of radiotracers in gas and oil industries include detection of lost drilling fluid, determination of drilling fluid invasion, location of cementing behind casing and channels, identifying the location of perforations and the thief zones. Similarly, the radiotracer applications in well stimulation operation include evaluation of hydraulic fractures and gamma logging. The radioisotopes used in the above applications include tritium,^{3}H (12.6 years, beta-energy: 0.018 (100%)), Iriduim-192, ^{192}Ir (half-life: 74 days, gamma energies: 0.110-1.378 MeV), scandium-46, ^{46}Sc (half-life: 84 days, gamma energies: 0.89 MeV (100%), 1.12 MeV (100%)), antimony-124,^{124}Sb (half-life:60.3 days, gamma-energy: 0.603 MeV (98%),1.691 MeV (47.57%)), gold-198, ^{198}Au (half-life: 2.7 days, gamma-energy: 0.41 MeV (99%)), silver-110m, ^{110m}Ag (half-life: 250 days, gamma-energy: 0.658 MeV (94.32%), 0.885 MeV (72.72%)) and iron-59, ^{59}Fe (half-life: 45 d, gamma energy: 1.1 MeV (55%), 1.292 MeV (44%)).

During EOR operations, water and gas are injected into the geological formation through injection wells to enhance the oil recovery. Radiotracers are extensively used for tracing movement of injected fluids that provide information about residence time, flow pattern, connectivity between production and injection wells and source of injected water. In addition, permeability, heterogeneity and orientation of fractures in the reservoirs can also be discerned using radiotracers. The information is utilized to evaluate performance of the fluid injection operation, optimize fluid injection and oil production rates; and validate the results of mathematical modeling. In addition to this, radiotracers are also used for estimation of residual oil saturation. The radiotracers commonly used in EOR operation include ^{3}H, carbon-14, ^{14}C (half-life: 5730 years, beta-energy: 0.156 MeV (100%)) and ^{131}I. The radiotracer applications in oil and gas industry are discussed in detail elsewhere [17, 18].

2.9 Wear and corrosion measurement

Wear and corrosion of metallic structures is a major problem in industry causing significant economic loss. Therefore, measurement of wear and corrosion rates is often required for quality control and durability of various mechanical tools. The conventional methods such as gravimetry, profilography, micrometry and replica methods are commonly used for the quantification of wear and corrosion rates. But these methods have many disadvantages such as low sensitivity, poor accuracy and cumbersome to be applied in many situations where the components need to be dismantled for each measurement. On the other hand, the radiotracer technique, known as thin layer activation (TLA) analysis, is a highly sensitive, online, accurate and easy to use even in complex industrial systems [19]. The technique can be applied to various components (iron, zinc, tin, silver, platinum, cadmium, lead, palladium, tantalum etc.) in oil and petroleum refineries, power plants, process and automobile industries. The methodology involves irradiation of a material with a beam of charged particles in an accelerator to produce radioactivity within a thin surface layer of the material (thickness of active layer: 10-300 μm). The radioisotopes produced depend on the chemical composition of the irradiated material. When a material having iron as a major constituent element is irradiated with a proton beam of energy 12-13 MeV, $^{56}Fe(p,n)^{56}Co$ nuclear reaction takes place producing cobalt-56 (^{56}Co) radioisotope. ^{56}Co has a half-life of 77.3 days and emits gamma rays of energy 0.847 MeV (100%) and 1.238 MeV (67 %)). Subsequently, the irradiated material is subjected to wear/corrosion by simulating the real time situation. As a consequence of wear/corrosion there will be loss of material as well as radioactivity from the surface of the component. The change in radioactivity with time is measured with a NaI(Tl) based or HPGe based gamma spectrometer. The radioactivity is converted to material loss and the wear/corrosion rate is quantified with the help of a calibration curve. The technique is widely applied in India for wear and corrosion rate measurements of several metallic components of technological importance.

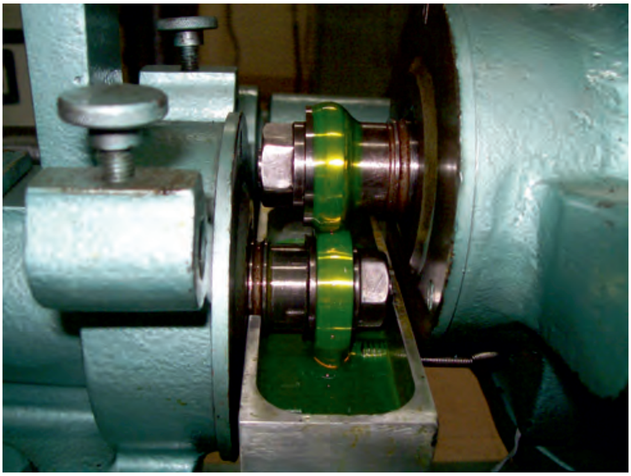

Figure 11: Application of TLA technique for wear rate measurement of automobile gears

Biswal et al. 2017 carried out a TLA study to estimate the wear rates of automobiles disc gears at different lubricating conditions [20]. Four different types of lubricants (TR-1, TR-2, TR-3, TR-4) were tested for their anti-wear behavior. The gears were made of EN31 steel with iron as a main constituent element. The gears were irradiated with 13 MeV proton beam using Pelletron accelerator facility, TIFR, Mumbai resulting in production of ^{56}Co. The irradiated gears were subjected to wear in a twin-disc tribo-tester simulating operating conditions of an engine by moving the two discs under lubricated condition (Fig. 11). The wear of the lubricated gears was measured periodically by measuring the loss in radioactivity within the disc gears during the testing. The activity of irradiated discs was measured by NaI(Tl) based gamma spectrometer. The wear testing and lubricating performance of the four different lubricants were carried out as a function of various parameters such as load, speed (rpm) and temperature. Based on the results, the lubricant TR-4 was found to have the best anti-wear performance at all the operating parameters used.

2.10 Radioactive particle tracking (RPT) technique

RPT is an advanced non-invasive velocity measurement technique that is used for flow visualization in laboratory and pilot-scale systems. In RPT, a single radioactive particle is used to mimic the phase whose velocity field needs to be mapped. In the case of liquid-phase tracking, the tracer particle is made neutrally buoyant, whereas in the case of solid phase tacking, the tracer particle should have similar properties (size, shape and density) as that of the solid phase. An array of strategically placed scintillation detectors around the system is used to track the motion of the radioactive particle (Fig. 12). The counts recorded by each detector are used to calculate the position-time series of the particle using a suitable reconstruction algorithm. The position time-series is further processed to calculate the instantaneous velocities, mean velocities, Reynold's stresses, granular temperature, trajectory length distribution, Hurts exponent and diffusivity, etc. The RPT technique is successfully applied to investigate the flow fields of different phases in various laboratory as well as pilot-scale process reactors such as gas-liquid reactor, gas-solid reactor, liquid-solid, and gas-liquid-solid systems [21]. A typical case-study is discussed below.

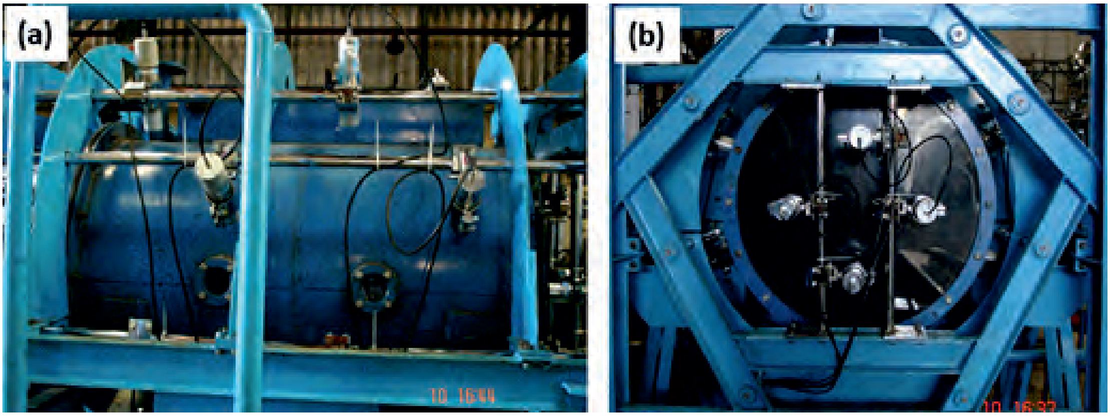

Figure 12: RPT setup in a bioreactor, (a) front view and (b) side view

The technique was applied to a pilot-scale bioreactor designed for the treatment of municipal wastewater [21]. Figure 12 shows the radiation detectors mounted around the bioreactor for the RPT measurements. The bioreactor is 800 mm in diameter and 1.2 m in length. A specific quantity of the media element is fed to the bioreactor based on the capacity and operating conditions. The municipal wastewater enters the bioreactor from the top of the reactor (left side) and exits the reactor from bottom (right side). Air is injected from the bottom of the reactor through four horizontally mounted rodes on the inner surface of the reactor. The air is injected tangentially from 5 mm holes made on these rods. This tangential entry of the air generates a circulating motion which generates an enhanced mixing and hence increases the mass transfer. The wastewater is treated aerobically in presence of the microorganisms that grow on the media elements. An adequate supply of air (oxygen) helps in the growth of the microorganism on the media elements which increases the water treatment capacity. In addition to this, uniform distribution of media elements and high mixing are critical for efficient operation of the bioreactor. Therefore, the RPT experiments were performed to track the motion of the media elements at different operating conditions. A single media element was tagged with a radioactive tracer particle (^{46}Sc) of activity 37 MBq and the same was introduced into the reactor. Twenty four radiation detectors were mounted around the bioreactor to track the motion of this media element as shown in Fig. 12. The RPT experiments were carried out at four different operating conditions. The data was acquired at a frequency 50 Hz for duration of 24-48 hours depending on the flow condition. After analyzing the data, velocity fields and tracer occurrences densities were obtained. Several flow abnormalities were identified which were primarily attributed to the poor design of the air-sparger used in the reactor. Several modifications in the design of the air-sparger were suggested and subsequently implemented based on the results obtained from the RPT experiments. After implementing the modifications, the efficacy of the reactor improved significantly leading to substantial technological and economic benefits to the industry.

2.11 Groundwater filtration velocity and direction

Groundwater is a valuable resource and its availability is declining all over the world because of over exploitation, contamination of the groundwater resources, climate change and many other human interventions. The poor planning of water resources besides natural stresses, like frequent failures of rainfall and geogenic contamination led to drying up of groundwater resources in India. Therefore, knowledge of groundwater recharge and its dynamics are important components needed for planning judicious management of groundwater resources. Groundwater dynamics can be assessed by residence / circulation time and transport (velocity) of groundwater. Among various methods, radiotracer based assessment of groundwater velocity achieve faster and precise estimates. Artificially produced and injected radiotracers are often used for measurement of groundwater velocities during investigation of a variety of hydrological problems [13]. In case of use of short-term studies gamma-emitting radiotracer such as ^{99m}Tc, ^{82}Br, ^{131}I are used. However, radiotracer such as chromium-51, ^{51}Cr (half-life: 27.7 days, gamma-energy: 0.32 MeV (10%)) and ^{60}Co are used in relatively long-term studies. Beta-emitting radiotracer such as tritium (^{3}H) is also used for long-term measurements of groundwater velocity. The use of beta-emitting radiotracer involves, collection of samples from the different monitoring wells at regular intervals and measuring the radiotracer activity using a liquid-scintillation counter in the laboratory.

There are two methods commonly used for the measurement of groundwater velocity using radiotracers, (i) Single well or point dilution method and (ii) Multi-well method. Single-well dilution method is the most commonly employed method for the measurement of groundwater

Figure 13: Groundwater velocity measurement

filtration velocity in hydrological investigations and development of civil engineering projects. The method involves drilling a borehole with perforations at the desired depth within the borehole, injecting the radiotracer, mixing the injected radiotracer homogeneously within the borehole, recording the radiotracer activity at different time intervals at a desired depth by lowering a waterproof scintillation detector. The recorded concentration is used to estimate the ground water velocity [22].

In case of multi-well method, the radiotracer is instantaneously injected into a well and its movement is monitored at one or more artificially constructed observation wells or naturally occurring springs located at different radial distance around the injection well. The monitoring is continued till the entire tracer is passed from the well. The distance between the injection and observation wells is of the order of a few meters depending upon the flow velocity. A distance of 2-5 m between the injection and observation well is sufficient if the movement of groundwater is slow (cm/d). Very low velocities and thus long observation time often make the multi-well technique impractical. Whereas, in case of higher velocities (m/d), the distances could be large, typically 10-50 m. Isotope and Radiation Application Division, BARC has carried out several groundwater velocity investigations at different locations in the country (Fig. 13).

3. Concluding remarks

- The radiotracer technology of industrial applications is well-established. The Bhabha Atomic Research Centre, Trombay, Mumbai has developed various radiotracer techniques and applied them in Indian industry for troubleshooting, measurement of process parameters and process visualization over the last five decades. The Indian industry has been enormously benefited from the application of the radiotracer technology and the cost to benefit ratio accrued in different applications varied from 1:10 to 1:5000.
- The Bhabha Atomic Research Centre, Trombay, Mumbai continue to pursue the research and development in the area of radiotracer technology. In addition to this, radiotracer laboratories have been established in various academic institutes in India with the support of Board of

Research in Nuclear Sciences (BRNS), Department of Atomic Energy (DAE) for their in-house applications.

- The transport and use of radiotracers in India is well-regulated and supervised by competent radiation protection agencies i.e. BARC-Safety Council (BSC), Mumbai and Atomic Energy Regulatory Board (AERB), Mumbai. With proper compliance of regulations and surveillance, the use of radiotracers does not cause any radiation hazards to public and users.
- The demand for application of radiotracer technology in India continue to grow but with a very slow pace and not commensurate with the size of the Indian industry. The applications are currently confined to only a few well-informed industries and a large section of the Indian industry is not aware about the potential of the radiotracer technology.
- Considering the size of the Indian industry, there is good scope for wider application of radiotracer techniques and can be effectively used to minimize shut down times of industrial plants; and improve industrial productivity and product quality thus leading to increased revenues for the industry.

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