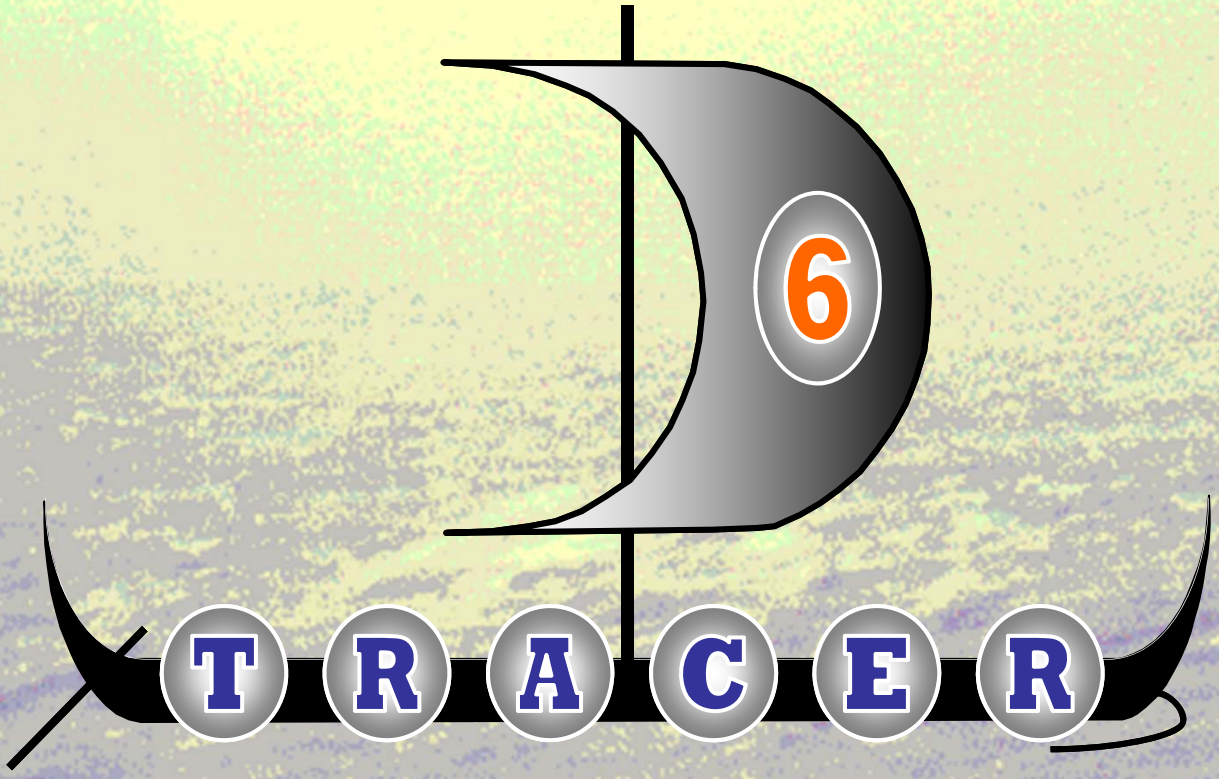
Abstracts

The 6th International Conference on Tracers and Tracing Methods, TRACER 6, Oslo, Norway, June 6-8, 2011



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Conference Theme

The primary objective of the ”Tracer” conferences remains to present the current status and trends on tracing methods and their applications. There will be opportunity for attendees from different fields to exchange scientific and technical information and knowledge about methods and applications in one field that may also be applied, with modifications, in another field.

The target participants are scientists, engineers and technologists in various areas of research and industry: chemistry and chemical engineering; metallurgy; environmental aspects; air and water quality; pollutant transport in soils, aquifers, rivers and the athosphere; bio-engineering and food engineering; pharmacy and medicine; petroleum industry etc.

Both fundamental aspects and industrial applications are planned to be covered. Advances in various fields will be high-lighted as shown below.

Development • New tracers (including radiotracers, chemical tracers, isotopic ratios, nanoparticles etc.) • Detection techniques and equipment (online, offline, scanning, camera, tomography, particle tracking, etc.) • Tracer methods (new methods and applications)	• Reactive tracer experiments and interpretation • Validation of computational fluid dynamics (CFD) simulations by tracer experiments • Numerical residence time distribution (RTD) • Data treatment and modeling
Applications • Pure science experiments • Industrial process equipment • Oil field evaluations and production • Geothermal energy development	• Geology and hydrogeology • Environment • Mineral and metallurgy processes • Pharmaceutical and medical examinations

Previous Events

- The first conference on “Tracers and tracing methods” was arranged in Nancy, France, in November 1998 as a national French event. The main organizer was Laboratoire des Sciences du Genie Chimique, CNRS-ENSIC.
- The second conference on the same subject was organized as an international event, also in Nancy and by the same main organizer as the first conference. It took place in May 2001.
- The third conference, briefly called “Tracer 3”, moved outside France to the small holyday resort city of Ciechocinek in Poland and was arranged in June 2004. The main organizer was Warsaw University of Technology.
- The fourth conference with the nickname “Tracer 4” moved back to France to the small village of Autrans and was arranged in October 2006. The main organizer was Commissariat à l’Energie Atomique, CEA, Grenoble.
- The fifth conference, “Tracer 5” moved outside Europe to the cultural heritage village of Tiradentes in the state of Minas Gerais in Brazil, and was arranged in October 2008. The main organizer was Centro de Desenvolvimento da Technologia Nuclear, CDTN, in Belo Horizonte, Brazil.

Svedberg's number playing a main role in diffusion processes

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Abstract
Since pioneering work on Brownian motion done by T. Svedberg in first years of 1900, the approximate number 1,54 has the meaning not only of mean number of colloidal random particles in a reticule but a deep property of spatial and time pattern of diffusion processes. In this paper is presented how this number put in a Poisson´s distribution may describe successfully particle dynamics not only in the so-called "diffusive period" (after Complete Mixing condition) but also in early period of plume evolution (Convective Period). This means that this last period is Gaussian also, against current picture of mass transport. An experimental proof of this statement is discussed.

Is storage mechanism in dead zone concept violating second principle?

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Abstract
As almost an axiom, current mass transport theories account for "Storage mechanism" in Dead zone concept as an objective, real thing. However, a closer analysis put in evidence some problems regarding second thermodynamic principle. This model, as least in conservative Taylor´s case, would seem developing with a lack of free enthalpy which converts it in an impossible manner. This fact may lead to consideration of plume Non-Fickian skewness as a virtual thing solved only by a Galilean composition. Some modeling regarding this effect are discussed in this paper.

Study of solid and liquid behavior in large copper flotation cells (130 m^3) using radioactive tracers

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Abstract

Industrial copper flotation is a complex separation process where solid fine particles are suspended in an aqueous pulp. Particles are selectively separated according to their superficial properties, by collection with air bubbles in mechanically agitated cells. The behavior of the solid and liquid phases, in large flotation cells, was characterized by means of the radioactive tracer technique. The use of radioactive tracers enabled the identification of the Residence Time Distribution, of floatable and non-floatable solid, from continuous (on-line) measuring at the output streams of the flotation cells. An advantage of using the radioactive tracer technique in flotation processes is the direct testing of the actual solid particles (similar physical and chemical properties, size distribution, shape, etc.), where tracer injection is almost instantaneous, because only a small amount of radioactive tracer is required. Another advantage is its capability for on-line measurements at various points inside the system without disturbances related to process sampling. For this study, the proper radioactive tracers were selected and applied in order to characterize the different phases; i.e. for liquid phase Br-82 as Ammonium Bromide, for floatable solid recovered in the concentrate Cu-64, and for non-floatable solid in three particle size classes (coarse: +150, intermediate: -150+45 and, fine –45 microns), Na-24. The selection of the non-floatable solid radioactive tracer considers several steps, because each particle size requires a certain tracer activity for injection in the flotation equipment. Each activity depends on the instrumentation characteristics and geometry of the system (i.e. cell size, piping) as well as the dilution the tracer will have in the process mass flow rate. Radioactive tracers were prepared by neutron activation in the 5 MW Nuclear Reactor of the Chilean Commission of Nuclear Energy. Activity (cps) was measured by scintillating crystal sensors of NaI(Tl) of 1”x1.5”, Saphymo Srat, thus allowing the simultaneous data acquisition of up to 12 control points, with a minimum period of 50 milliseconds. The experimental results confirmed the strong effect of particle size in the Residence Time Distribution, and mean residence time of solids in larger flotation cells, and consequently in flotation hydrodynamics. From a hydrodynamic point of view, the experimental data confirmed that a single mechanical flotation cells, of large size, can deviate significantly from perfect mixing. The experimental work was developed in a 130 m^3 industrial flotation cell of the rougher circuit at El Teniente Division, Codelco-Chile.

Keywords: *froth flotation, RTD, radioactive tracer, flotation cells, modelling*

A thermodynamic view of tracer plume evolution: Complete mixing condition evaluation

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Abstract

One of most controversial issues of modern tracer theory is the "complete mixing condition" because of its importance in evolution of hazardous solutes in natural flows. This condition named also as "Mixing length" measures the distance from pouring point when tracer particles have spread uniformly on cross section of stream. The point is that until now there is no rational, complete and easy to use formula to calculate it. Rather, this condition is evaluated mostly by means of empirical relationships; among them Ruthven´s is one of current usage. Also there are statistical methods that, applied by software packages, allow to characterize this condition. However a new focus on this issue is important, because it is necessary to tie together generality, easiness and accuracy. This paper puts on discussion a thermodynamics method to understand when a tracer is in this remarkable condition. Herein it is developed the conditions when this method may be applied. It is shown also how the resulting formula is convergent with Ruthven´s equation. An experimental demonstration is presented.

Using isotopes produced from radionuclide generators as tracers for membrane installation investigation

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Abstract

Radiotracer technique is a useful method for measurement of liquid phase flow rate in membrane modules, as well as for studying the phenomena occurring during filtration.

There are many methods used for investigation of phenomena taking place in membrane permeation but very often they have fundamental restrictions, e.g. such optical methods as Direct Visualization Above the Membrane (DOTM) or Direct Observation Through the Membrane (DVAM) as well as laser methods like laser triangulometry require membrane modules used in experiments to be transparent or having windows made of glass. Whereas other techniques like Small-Angle Neutron Scattering (SANS), Magnetic Resonance Imaging (MRI) or Electrical Impedance Spectroscopy (EIS) are expensive and requiring sophisticated equipment.

Tracer techniques, which are non-invasive methods are the alternative for the study of processes proceeded inside the membrane apparatus. They do not require special equipment to be used. Furthermore, radiolabelled compounds have an advantage over non-active tracers because of very high sensitivity of detection, which gives the opportunity for using very low concentration of the tracer, as well as for remote detection of radiation through the layers of other materials present in the apparatus. Therefore, the material which membrane module is made from is unrestricted.

The aim of the work was investigation of membrane apparatuses using such short-lived isotopes as Ba-137m and Ga-68 as the tracers. These isotopes were obtained from radionuclide generators: Cs-137/Ba-137m and Ge-68/Ga-68. The first of these radionuclides: Ba-137m with half-life of 2.55 minutes was applied as the liquid phase tracer for investigation of hydrodynamic conditions inside the membrane apparatus. Two membrane modules, the first one with metallic membranes and the second with the ceramic membrane in which the mean residence time equalled respectively: 4 - 14 s and 1.4 – 7.2 s were tested by using Ba-137m. The experiments showed that radionuclide with such a short half-life is a perfect tracer of the liquid phase. It can be successfully used for investigations of the membrane modules with short time of residence of the media inside the apparatus. Moreover, the application of such a radiotracer does not result in long-lasting contamination of examined apparatus.

Whereas Ga-68 with longer half-life equal to 68 minutes was considered as the solid phase tracer in order to get some information about the phenomenon occurring in the membrane boundary layer. After preparatory stage, namely kinetic studies of isotope adsorption into the carrier material, the rate of growing of the deposit layer as well as its thickness on the flat sheet membrane was studied. The influence of such process parameters like pressure, linear velocity and feed concentration on formation of the bentonite layer on the membrane surface was studied.

Elaborated techniques can be useful for membrane processes control to prevent the fouling phenomenon and permeate flux decline in membrane filtration apparatuses.

Two coordinate mass transport in streams: Longitudinal dispersion Coefficient as time function version

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Abstract
A controversial issue in current mass transport theories is the constancy of Longitudinal Dispersion Coefficient, E, whereas the main reason to accept this requirement is that equations operates properly if there is uniform flow and then E coefficient is a constant. But it is evident that this regime is seldom found in Nature, and then it is very difficult to accept this constancy as regular issue, being rather an exception. In this paper is explored a view of this coefficient as function of time as a means to void this contradiction. For this purpose it is explained how a two dimensional transport may be expressed as one dimension equation with a time dependent coefficient. Also it is discussed how E should be a time function from thermodynamic point of view.

Scintillating setup for low activity radiotracer detection in underground galleries

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Abstract

Radiotracer studies are of great interest in studying deep underground clay layers for future long term nuclear waste storage. For that, there is a need of very specific low profile high sensitivity radiation sensors.

We have developed a new family of miniaturized setups for the detection of ionizing radiation. The device consists in a plurality of high accessibility scintillation probes. Each probe is made of a scintillating crystal optically coupled to several optical fibers. The coincidence readout of the sensors increases the ability to count low ionizing radiations flux (low energy and activity; < 1 count /s).

The first experiment using this device will be presented. This application aims to study the diffusion of beta emitter tracer (^{36}Cl, E_{max} 710 keV) in geological clay layers, in order to simulate a leak of radioactive wastes stored in underground sites. The global system, including photodetectors and electronics, will be installed in an underground gallery, and the probes will be inserted in 20 m long, 20 mm wide drillings in the clay. The use of optical fibers allows a maximum compactness of the probes, as well as to allow a human access to the detection system (photodetectors and electronic of acquisition), which is needed for recalibration and control during the 5 year long study. The preliminaries study of a second experiment will be introduced. This application aims to study the diffusion of ^{22}Na in this same kind of matrix. SiPM based detector has been developed to optimise the detection of 511 keV gamma photons in long underground drillings.

SiPM detectors for ionizing radiations detection

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Abstract

AXINT have developed a new range of miniaturized gamma detectors which can be used with any gamma ray detection application (radiotracers or sealed source applications).

The device consists in a very compact, high efficiency detector that can be used for counting or energy measurements. Each probe is made of a high density detection crystal given a high sensitivity to the detectors. A SiPM is used as photodetector. This readout allows compact and light design, stable toward temperature and magnetic fields variations, without high voltage power supply. All the probes used by a same setup are connected to a single datalogger that concentrates the data of the different probes before treating and sending them to a computer.

All the electronics and DAQ are integrated in each probe. So, one probe is equivalent to a global photomultiplier, pre-amplifier, amplifier and counter system, with a much greater compactness and adaptability.

Therefore, one can change the dimensions of the detector, the composition of the crystal, the DAQ itself, in order to detect particular tracers in particular environments. Theses skills can find direct utility to the various applications proposed in radiotracers setups.

Calcite scale prediction at the near-well region: A radiotracer approach

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Abstract

To assess a calcite scale problem and manage deposition, it is important to know when, where and how much $CaCO_3$ will be deposited during oil production. Effective prediction of scaling requires a reliable thermodynamic model for the prediction of the scaling tendency, a kinetic model for the prediction of scaling rate and a transport model to simulate flow in a porous medium. The accurate prediction of the scale deposition can warn the engineers to 'treat' the formation around the wellbore in time. In addition, the prediction of the distribution of the scale deposition can direct the engineers to ensure the placement of the inhibitors into the formation zones where the deposition is expected, thus maximizing the probability of successful prevention of formation damage and minimizing at the same time the amount of the required inhibitors.

In this contribution, we present a geochemical computational model that combines existing thermodynamic and kinetic models for $CaCO_3$ precipitation, with treatments of flow and diffusion in electrolyte systems, in a one-dimensional porous medium. The geochemical model has the ability to predict the distribution of scale deposition along and around the production wells, as well as the distribution of formation damage (pore blocking, permeability reduction) around the wells. Evidently, in our approach we mainly address the advective part of the flow, rather than attempting a detailed investigation of how microscale fluid mechanics affect precipitation.

The development of the geochemical model was based on scale reaction calculations attempting to simulate/interpret dynamic tube-scale laboratory experiments. The laboratory scale data have been acquired from a series of sandpack blocking experiments using for the first time a radiotracer technique. In particular, the formation of $CaCO_3$ scale is monitored by measuring the activity of ^{47}Ca in the deposit. The new data are incorporated into existing calcite kinetic models to check their performance. Finally, we demonstrate how the geochemical model can be used to predict oilfield calcite scale profiles.

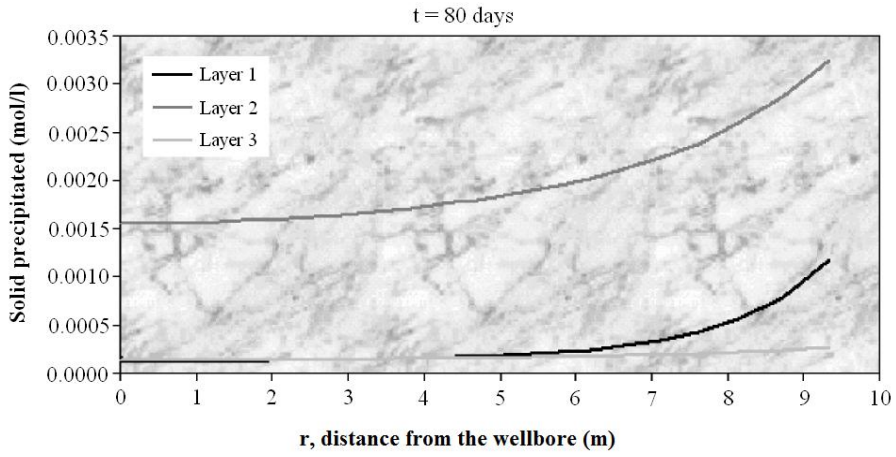

Figure 1. $CaCO_3$ precipitation 80 days after start of simulation of the well 15/21a – IB27 in Ivanhoe field.

Simultaneous use of tracers for measuring flow parameters in a river and evaluation of radiological impacts on fishes

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Abstract

There are few experimental data in the literature related to the impact of tracer tests in water environment, specially the radioecological impact on the biota. As part of an IAEA Regional ARCAL Project in Latin America – RLA/1/010 "*Mejora de la Gestión de la Contaminación de Masas de Aguas Superficiales Contaminadas con Metales*", field experiments using simultaneously two of the water tracers: radioactive ($^{99m}TcO_4^-$), chemical (NaCl) and fluorescent (Rhodamine WT) were performed in Antas Creek, Poços de Caldas, Brazil. These experiments supplied the data (longitudinal dispersion and dilution coefficients and flow rate) to be used in a mathematical model to evaluate water quality and allowed comparing the performance of the tracers.

In parallel with the tracer experiments, the evaluation of radioecological impacts of ^{99m}Tc on fishes was made. It consisted of laboratory and field experiments aiming at determine the bioaccumulation factor. In the laboratory experiments an activity of 10 µCi was diluted in a 15 L aquarium and 40 *Brachydanio rerio* fishes (total weight of 10.9 g) were placed during one hour. In the field experiments netted fish corrals containing some *Poecila reticulata* fishes were placed in two measuring stations during the passing of the ^{99m}Tc tracer plume. In both cases the fishes and water samples were analyzed by gamma spectrometry.

One conclude that the three tracers provided similar results and the radioecological impacts on the fishes were negligible. For the laboratory experiment the absorbed dose rate was 4.24 µGy/d and for the field experiment of 05/18/2010, when an activity of 380 mCi of ^{99m}Tc was injected in the Antas Creek, they were 4.20 µGy/d (Station D1) and 1.26 µGy/d (Station D2), lower than the limit for background (10 µGy/d), according to ICRP (2009).

Table 1. Main results of the tracer experiments between stations D1 and D2.

Tracer	Date	Flow velocity (m/s)	Dispersion coefficient (m^2/s)	Dilution coefficient	Flow rate (L/s)
^{99m}Tc	05/18/2010	0.14	0.70	1.5	
Rhodamine WT	05/18/2010	0.14	1.08	1.7	Station D1 = 258 Station D2 = 512
^{99m}Tc	05/19/2010	0.16	1.05	1.28	
NaCl	05/19/2010	0.16	0.9	1.28	

Strontium isotopes as natural tracers in oil reservoirs

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Abstract

Tracers are used to assess diverse operations performed during oil production from reservoirs. One main process is to inject water, aiming at expelling the oil from the rock pores and driving it all the way to the production wells. Tracers have been frequently used to evaluate the characteristics of the ensuing flow. Taking into account the complexity of the reservoir system it is desirable to have a diversified menu of tracer at one's disposal. In this connection radioisotopes added as labeled chemicals to the injected water have proved to be especially effective in tracing the water phase. However, their utilization may be restricted due to safety requirements or difficulties related with their measurement, such as background radiation, intervening chemical and physical changes, exceedingly long half-life, and the like. Natural water-soluble isotopes can be an interesting alternative to avoid some of these problems; inasmuch as they occur in the original reservoir waters they do not need to be added or otherwise manipulated. Strontium isotopes can be one such choice. Strontium occurs in many rocks hosting the reservoir and has four stable isotopes: ^{84}Sr, ^{86}Sr, ^{87}Sr, and ^{88}Sr. One of these, ^{87}Sr, is radiogenic; it is produced by beta decay from ^{87}Rb. Rubidium is also found in reservoir rocks. When leached by the saline waters it will increase the $^{87}Sr/^{86}Sr$ ratio. On the other hand surface waters, especially ocean waters, do not have the same intimate contact with rock formations; therefore their $^{87}Sr/^{86}Sr$ ratio is significantly lower.

During this process the injected water mixes with the original highly saline water originally present in the reservoir as the reservoir becomes progressively flooded. However, at the start of the water injection process a plume will of less saline water be formed inside the reservoir, and a steep gradient isotope ratio gradient may be formed at its front, depending on the relative magnitudes of these ratios in the injected and reservoir waters. The idea is monitor the isotope ratios and concentrations in producer wells; they may show a noticeable decrease as the injected water breaks through this well, and important milestone in oil recovery operations. Besides, breakthrough times also provide an indication of well-to-well interconnection and transit times.

An attempt was made to investigate the capability of basic ICP-MS equipment, with a relative standard deviation: $0.1\% < RSD < 0.5\%$, to detect the breakthrough of injected water. The results were compared with a tritiated water tracer experiment. The same samples used for counting the tritium level in the water flowing out of a producer well were mass analyzed for the $^{87}Sr/^{86}Sr$ ratio and for total strontium concentration. Rubidium had to be separated in special ion-exchange columns to avoid isobaric superposition.

Even though the $^{87}Sr/^{86}Sr$ ratios in the injected and reservoir waters were not too different, some trends could be observed in the results that point to utility of the method. This performance can be improved using a TIMS spectrometer ($RSD < 0.01\%$), but at a higher cost and analytical effort.

On the other hand, the total strontium concentrations proved to be a quite viable tracer for breakthrough detection. Since the strontium concentration in seawater is fairly constant and significantly lower than that of reservoir waters, the presence of the latter in the producer well can be securely (and less tediously) disclosed using the basic ICP-MS equipment.

Transport study in unsaturated porous media by tracer experiment in a dichromatic X-ray experimental device

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Abstract

Assessing contaminant migration in the context of waste disposal, contaminant migration in soils or environmental remediation of polluted soils requires a complete understanding of the underlying transport processes and reliable predictive models. To validate these models and acquire transport parameters, a novel experimental device BEETI has been specifically adapted to assess the spatial-temporal dynamics of tracers in relation to the porous media geometry and the physico-chemical conditions. This device, equipped with a scanning dichromatic X-Ray spectrometer, can simultaneously measure solid density, solution content and tracer concentration at selected locations within a vertical column filled with porous materials. X-ray measurements are non-invasive and non-destructive. Tracer migration is induced by a controlled solution flow. X-ray spectrometry allows assessing the spatial solute dynamics, and thus the transport parameters, all along the column, conversely to standard breakthrough analysis, which is limited to the column outlet. Experimental estimates of first- and second-order moments of the contaminant concentration allow the accurate evaluation of residence times and dispersion coefficients of the tracers. Transport parameters can be also determined by using a numerical model on the experimental data.

In unsaturated context, hydraulic parameters characterizing the porous media, are easily determined by water content measured all long the column at imposed head. A tracers downwards experiment is performed to follow tracers displacements along homogeneous sand column partially unsaturated (water content gradient). Water content, tracers concentration profiles, Darcy flow velocity and breakthrough curve are experimentally measured. Water content appears as the most important parameter to simulate the tracer migration due to its direct impact on the tracer pore velocity. In this experimental condition, the pore velocity is calculated either Darcy flow velocity and water content or resident time and water content. Use of Hydrus 1D permits the simulation of tracer concentration profiles inside the column, taking into account the Darcy flow and the measured water content. In this context, we show that a water content error higher to 5% switches the simulated fitting curve from experimental data and limits the transport parameter determination with better accuracy.

Gas Phase Mixing in Bubble Columns with Internals

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Abstract

Despite the tremendous applications of bubble columns equipped with internals for heat removal, there is a lack of fundamental understanding of the effect of these internals on the hydrodynamics and mixing patterns. In this work, the effect of internals on the gas phase mixing and overall gas holdup has been investigated in 0.19 m diameter bubble column with and without internals using an air-water system with superficial gas velocities ranging from 3 to 45 cm/s covering both the homogenous and heterogeneous regimes.

A well developed gaseous tracer technique was used to measure the residence time distribution of the gas phase. This method offers an advantage over other gas tracer techniques since it yields an accurate estimation of the RTD of the gas phase as it accounts for the extra dispersion that occurs due to the non-ideal tracer injection and the extra dispersion in the plenum, sampling, and analysis systems which causes significant measurement errors if they are not accounted for. The extra dispersion in the plenum is accounted for by assuming a CSTR model for the plenum and experimentally characterizing its residence time. The extra dispersion in the sampling and analysis system is removed by independently measuring the RTD of the sampling system and deconvoluting it from the overall RTD of the system. Data analysis was accomplished by assuming two different models for the reactor, namely, the axial dispersion model and the 2D convection diffusion model.

Results indicate that the presence of high percentage of internals causes an increase in the overall gas holdup and a significant decrease in the extent of gas phase backmixing.

Experimental and Numerically Predicted Residence Time Distribution in Chemical Reactors

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Abstract

The quantitative description of mixing is a key subject of chemical reaction engineering. The concept of residence time distribution (RTD) arising from tracer experiments can be used to quantify mixing. The experimental RTD allows determining some global parameters as mean residence time, standard deviation and flow detection through stagnate zones or bypasses. More fundamental information concerning flow patterns and mixing can be obtained through numerical simulation tools - computational fluid dynamics (CFD) for example. Increasing numbers of studies on flows in reactors using CFD have been reported in the last decade. Currently, CFD methods constitute very powerful tools and are in common use for flow patterns prediction. Anyway, in majority of cases the CFD results have to be validated by experimental measurements. The experimental RTD method, among others, can be used for this validation. In CFD codes the RTD function can be simulated utilizing the particle tracking method. Since the RTD concept is not common in fluid dynamics studies, many CFD codes require some supported software for RTD simulation.

The paper will present the particle tracking method for RTD simulation using FLUENT® CFD software supported by MATLAB® codes. Two case studies comparing the experimental and simulation RTD results will also be presented. The first will present the laboratory jet mixer and the second - the industrial gold leaching tank study.

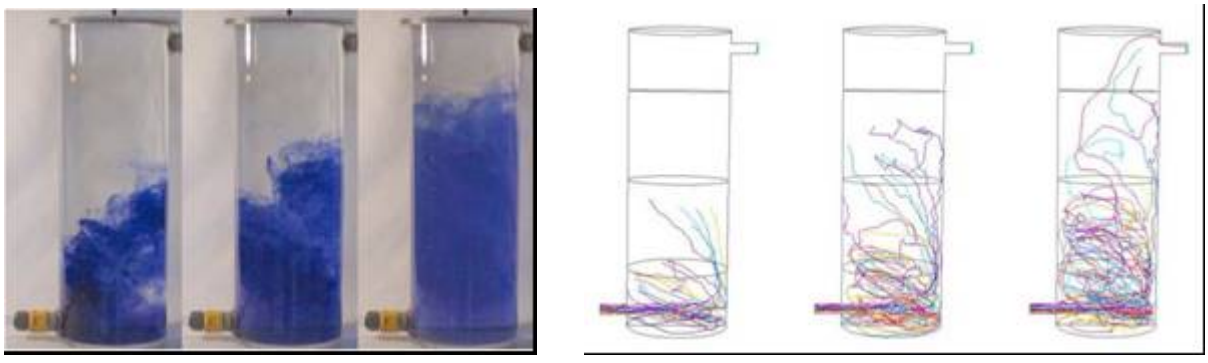

Figure 1. Experimental and simulated tracer flow visualization. Progress of dye tracer in the reactor at 8, 16 and 24 s after pulse feed.

Using tomography technique to trace the distribution of solid particles in a slurry reactor

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Abstract

Solid-liquid mixing is one of the most important mixing operations because it plays a crucial role in many unit operations such as crystallization, suspension polymerization, water and wastewater treatment, adsorption, dissolution, dispersion of solids, and leaching. Different techniques (e.g. laser beam, refractive index, conductivity probe, and sampling method) have been employed to measure the degree of solid suspension, which is a vital parameter in characterization of the solid-liquid mixing operations. Most of these techniques cannot be employed for the opaque slurries and some of them are intrusive. In this study, Electrical Resistance Tomography (ERT) was utilized to trace the distribution of solid particles in a slurry reactor equipped with a top-entering axial-flow impeller. This technique does not disturb the generated flow pattern and is very useful when the measurement of the solid distribution at highly concentrated slurries (opaque systems) is required The tomography images were utilized to obtain the axial solid concentration profiles by which the degree of homogeneity was quantified as a function of the impeller power/speed, impeller type, impeller off-bottom clearance, impeller pumping direction, particle size, and solid concentration. The ERT sensor planes were positioned around the circumference of the mixing tank. Each plane had 16 stainless steel sensors which were situated at equal interval on tank periphery. The electrodes were in contact with the fluid but did not disturb the flow pattern generated by the impeller. To trace the distribution of solid particles, the adjacent measurement protocol was employed. The current was injected using a pair of neighbouring electrodes and voltage differences were measured using the other pairs of neighbouring electrodes. To repeat this process, current was injected using all other possible pairs of neighbouring electrodes until all the independent measurements were made. The linear back projection algorithm was used to convert the voltage measurements to conductivity values using sensitivity matrix. The calculated conductivity was then converted to solid concentration through Maxwell's equation. To determine the axial solid concentration profile, the average solid concentration was computed for each ERT plane and the results were then normalized to the overall average concentration of solid particles within the tank. The axial concentration profile was used to calculate the degree of homogeneity for the slurry reactor as a function of the operating conditions and design parameters. The results showed that the level of homogeneity in a solid-liquid mixing system improved with the increase in impeller speed. However, after achieving the maximum level of homogeneity, any further rise in the impeller speed had a detrimental effect on the level of homogeneity. The ERT data were utilized to characterize and optimize the mixing performance in a slurry reactor. Applying the finding of this study will lead to improved equipment design, chemical cost reduction, increased production rate, improved quality of products, and more efficient use of power in slurry reactors.

Using a tracer technique to identify the extent of non-ideal flow in the continuous mixing of non-Newtonian fluids

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Abstract

Continuous-flow mixing operation is widely used in many processes such as polymerization, fermentation, wastewater treatment, and pulp and paper manufacturing. Continuous-flow mixing systems have several advantages over batch mixing operations as they provide high production rates, improve process control, and save operation time and labor cost by eliminating loading and unloading materials and between-cycle cleaning. The non-Newtonian fluids with yield stress such as pulp suspension, food substances like ketchup and mayonnaise, paints, cement, pigment slurries, certain polymer and biopolymer solutions, and wastewater sludge are frequently encountered in chemicals and allied industries. Study shows that non-ideal flow such as channeling, recirculation, and dead zones significantly affect the performance of continuous-flow mixing of pseudoplastic fluid possessing yield stress. To study the dynamic behavior of the continuous-flow mixing process, the xanthan gum solution, which is a pesudoplastic fluid with yield stress, was agitated in a flat-bottomed cylindrical tank equipped with a top-entering impeller. The dynamic testing was performed by exciting the system and observing the input and the output conductivities over a specified time interval. The system was excited by injecting the saline solution (as a tracer) into the fresh feed stream prior to being pumped into the mixing vessel using a metering pump. The injection of the tracer was controlled by a computer-controlled on-off solenoid valve. The conductivity values of the input and output streams were measured as a function of time using the flow-through conductivity sensors, which were recorded using a data acquisition system to estimate the dynamic model parameters. The experimental procedure consisted of: (1) exciting the system by a rectangular pulse, (2) designing a frequency-modulated random binary signal on the basis of the response of the system to the rectangular pulse by concentrating the excitation energy at frequencies where Bode plot was sensitive to parameter variations, (3) exciting the system by a frequency-modulated random binary signal, and (4) validating the dynamic model with a new input imposed by another random exciting signal to generate a new output and then comparing the measured and predicted outputs. The extent of non-ideal flows was quantified using a dynamic model that incorporated channeling, recirculation, and dead volume in the mixing vessel. The dynamic model parameters were estimated using the numerical method that employed an optimization technique to solve the constrained nonlinear problems. This method used a least squares minimization for the optimal delays, followed by an accurate gradient search for all parameters using sequential quadratic programming (SQP) method. The effects of important parameters such as impeller type (axial flow impellers: A100, A200, A310, A315, A320, 3AH, and 3AM; radial-flow impellers: R500, RSB, Rushton turbine, and Scaba) and impeller speed on the degree of channeling and the fraction of fully mixed volume were investigated. The results showed that the A320 impeller was the most effective among the axial-flow impellers and the Scaba impeller was the most effective among the radial-flow impellers to reduce the non-ideal flow in the continuous-flow mixing system. The optimum impeller speed at which the channeling approaches to zero and fully mixed volume approaches to the total volume of the fluid within the mixing vessel should be chosen, as further increases in impeller speed may lead to more power consumption for the same extent of the fully mixed volume.

Simulation and interpretation of inter-well tracer tests

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Abstract

In inter-well tracer tests (IWTT), chemical compounds or radioactive isotopes are used to label injection water and gas to establish well connections and fluid patterns in petroleum reservoirs. Tracer simulation is an invaluable tool to ease the interpretation of IWTT results and is also required for assisted history matching application of tracer data.

In this paper we present a new simulation technique to analyse and interpret tracer results. Laboratory results are used to establish and test formulations of the tracer conservation equations, and the technique is used to provide simulated tracer responses that are compared with observed tracer data from an extensive tracer program.

The implemented tracer simulation methodology use a fast post-processing of previously simulated reservoir simulation runs. This provides a fast, flexible and powerful method for analysing gas tracer behaviour in reservoirs. We show that simulation time for tracers can be reduced by factor 100 compared to solving the tracer flow equations simultaneously with the reservoir fluid flow equations. The post-processing technique, combined with a flexible built-in local tracer-grid refinement is exploited to reduce numerical smearing, particularly severe for narrow tracer pulses.

The paper contributes to improved and rapid tracer simulation, important for correct interpretation of tracer results from inter-well tracer tests in petroleum reservoirs. The formulation of the equation and the simulation techniques described is also valid for other applications, such as water tracers, CO_2-sequestration and non-aqueous phase liquids.

PEPT: an invaluable tool for 3-D particle tracking and CFD simulation verification in hydrocyclone studies

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Abstract

Cyclones are used extensively for separation or classification of phases according to density, e.g. for gas-solid, liquid-solid, and liquid-liquid separations, where the cut-size requirement for the dispersed phase particles (bubbles, drops or solid particles) is down to few microns. Whenever the carrier phase is a liquid, they are referred to as hydrocyclones.

The flows of the phases in hydrocyclones have been studied widely. However, the flow field alone cannot reveal the complexity of interaction between the liquid and particles, while this is crucial for separation efficiencies. Knowledge of the particle history, i.e. the trajectory, in hydrocyclones is therefore essential for understanding the root causes for the cyclone performance, as well as for instigating and verifying new and improved cyclone designs.

Some researchers have reported particle trajectories calculated using CFD simulations. However, experimental visualization of particle trajectories are scarce because of the difficulties in tracking fast-moving particles in 3D in hydrocyclones due to limitations in spatial and temporal resolutions, as well as limitations in the available detection techniques. In this paper we report and compare particle tracks in a hydrocyclone generated both numerically with Eulerian-Lagranian CFD and experimentally by positron emission particle tracking (PEPT).

A hydrocyclone with a cylinder-on-cone design was used in this study. The geometries used in CFD simulations and experiments are identical. In the PEPT experiments, a strong-base anion exchange resin bead was labeled with a positron emitting isotope ^{18}F. After emission, the positron annihilates with a nearby electron, which generates two gamma-photons transmitted in back-to-back directions defining a "line of response" (LOR). The position of the resin bead can be found by cross-triangulating the numerous LORs detected within a short time interval, e.g. a millisecond, using our developed algorithm.

The 3-D particle trajectories were generated using the Large Eddy Simulation (LES) turbulence model for the fluid and Lagrangian tracking for the particles.

Figure 1 (a) shows a trajectory obtained by PEPT. Each point represents a millisecond particle position. The CFD simulated particle trajectory is shown in Figure 1 (b).

In this work, PEPT is utilized to track a fast-moving particle in 3D in a hydrocyclone with very high temporal and spatial resolutions. The behaviors of the particles are analyzed in detail and are found to be consistent between experiments and CFD simulations.

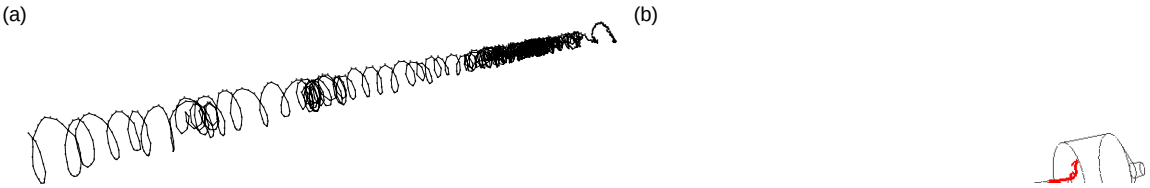

Figure 1.

Green tracers for dynamic characterization of water bodies and oil reservoirs

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Abstract

The definition and preservation of the volumes of groundwater sources and also the management of water resources used in oil production are essential. Tracers are now a very important characterization tool and have become indispensable due the lack of direct access to these formations and the inexistence of any other detector that permeates through the channels of the rock formation. As a result of climate change, the industries have sought the eco-efficiency through a review of concepts and processes in order to adapt them to this urgent need. In this context, the tracers are presented as an important tool for environmental control and whose purpose is to allow the hydrodynamic characterization with minimum environmental impact. This accounts for an increasing search for green tracers, or environmentally friendly. The selection of tracers for a particular application is made initially through the adequacy of product to the prerequisites described in the literature and then subjecting the selected substance tests of rock-fluid interaction in the specific conditions of application. In this line, this work presents a renewed discussion of these prerequisites for tracer selection within the concept of sustainability. It then presents a methodology for selection of tracers more environmentally correct. As a result of using this methodology is presented a tracer tested in laboratory and field tracer in parallel with other already established in the literature. Finally, it is presented the results of the characterization of an oil field area with horizontal wells with this tracer selected. The injected tracer supplied information regarding the fluid distribution and trajectory characteristics involved, defined directional flow trends and facilitated the assessment of how to effectively sweep the analyzed area. This information is crucial to reservoir management and complements other high-impact measures to assess the effectiveness of water injection in horizontal wells drilled in this field reactivation phase. In addition to the technical contribution to field hydrodynamic evaluations, this study presents a scientific contribution to reassess tracer conventional concepts within the new scenario of much stricter environmental requirements.

The use of chemical tracers to water injection processes applied on Romanian reservoirs

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Abstract

The hydrocarbon reservoirs are extremely complex, each reservoir having its own identity. Reservoirs heterogeneity (mainly regarding the layered ones) frequently results in low recovery efficiencies, both under the primary regime and when different agents are injected from the surface.

EOR processes efficiency depends on how detailed the reservoir is known and on the information related to fluids flow through reservoir. There are certain analyzes, investigations and tests providing good knowledge about the reservoir. The tracer tests are among them, being frequently used to water injection processes.

Depending on the method used, IWTT (Interwell tracer test), SWTT (Single-Well Tracer Test), TWTT (Two-Well Tracer Test), information are obtained as related to: the setting of the preferential flow path of the injected fluid, the identification of water channels, evidencing the geological barriers, determining the residual oil saturation, around the well bore or along the tracer's path between two wells.

This paper is focused on ICPT Câmpina efforts related to the use of the chemical tracers to the water injection processes applied to the oil reservoirs of Romania. It describes the usual tracers and the methods used to detect them in the reaction wells.

Up to now, more than 45 tests with IWTT tracers have been performed on-site and this work presents some of their results.

Determination of residence time distributions in different high pressure gasification processes

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Abstract

The production of synthesis gas is one of the first steps in the conversion of different feedstocks to liquid fuels like methanol or gasoline. Feedstocks might be gaseous (e.g. natural or flare gas), liquid (e.g. heavy oil residues) or solid (e.g. coal or biomass). At TU Bergakademie Freiberg in Germany, a test plant with 5 MW thermal power has been installed and operated together with Lurgi GmbH (part of Air Liquide Group) for the conversion of gaseous and liquid fuels. It is designed for three different modes: the so-called ATR-mode (Autothermal Reforming), the Gas-POX-mode (Partial Oxidation of natural gas) and the MPG-mode (Multi-Purpose Gasification). The first one is a process for the catalytical conversion of natural gas and can be run at pressures of up to 70 bar(g). The Gas-POX-mode is also used for natural gas processing, but no catalyst is used and pressures may reach up to 100 bar(g). In MPG-mode, high-viscosity liquids can be gasified at pressures of up to 100 bar(g). In all modes, the feedstock is processed with oxygen and steam.

Because of high investment costs for such processes, design studies with the help of computational fluid dynamics (CFD) are of increasing importance. Validation of such studies is very complicated due to high pressures and temperatures within the reactor and the poor accessibility of measurement equipment. The usage of radioactive tracer material has been determined as a possible way for obtaining information on flow conditions within the reactor. Experiments have been conducted for all three modes explained above.

The radioactive isotope ^{41}Ar (half-life 1.83 hours) has been used for the measurements. Scintillation counters were installed outside of the reactor at different heights to measure gamma radiation. The method of momentum (MOM) was used to derive residence time distributions out of the measured values.

The quality of measurement of residence time is different for the three processes. In ATR-mode, a large reactor volume and height in combination with the homogenization of the flow by the catalyst bed make it possible to determine the residence time distribution of the complete reactor. In Gas-POX- and MPG-mode, the reactor dimensions were strongly reduced for these experiments. Additionally, due to the lack of homogenization, the actual velocities within the reactor are much higher compared to the ATR-mode. Thus, measuring accuracy is considerably reduced.

CFD calculations were also performed. The CFD model was validated by comparing the residence time calculated with the experimentally measured one. A reasonable agreement was found, however, some problems with the accuracy of the experiments were found - besides some other parameters - in dependence of the operation mode of the gasifier. As a conclusion, the radiotracer method in general is well suited for investigation of high pressure gasification processes.

Investigation of liquid phase axial dispersion in Taylor bubble flow by radiotracer residence time distribution analysis

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Abstract

A gas-liquid Taylor bubble flow occurs in small diameter channels in which gas bubbles are separated by slugs of pure liquid. This type of flow regime is well suited for solid catalyzed gas-liquid reactors in which the reaction efficiency is strong a function of axial dispersion in the regions of pure liquid. This paper presents an experimental study of liquid phase axial dispersion in a Taylor bubble flow developed in a horizontal tube using radiotracer residence time distribution (RTD) analysis. A parametric dependence of axial dispersion on average volume fraction and phasic mass fluxes was also investigated by varying the relative volumetric flow rates of the two phases. Holdups of liquid phase and its flow velocities are also reported. ^{137m}Ba produced from a ^{137}Cs/^{137m}Ba radionuclide generator was used as radiotracer and measurements were made using the NaI(Tl) scintillation detectors. Validation of ^{137m}Ba in the form of barium chloride as aqueous phase radiotracer was also carried out. Axial Dispersion Model (ADM) was used to simulate the hydrodynamics of the system and the results of the experiment are presented. It was observed that the system is characterized by very high values of Peclet Number (Pe ~ 10^2) which reveals an approaching plug type flow. The experimental and model estimated values of mean residence times were observed in agreement with each other.

Keywords: *Axial dispersion, Taylor bubble flow, Radiotracer, Residence Time Distribution (RTD)*

Radiotracer investigations to study the hydrodynamic characteristics of continuous phase in a pulsed sieve plate extraction column

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Abstract

The present investigations are focused to study the hydrodynamic characteristics of continuous phase in a pulsed sieve plate extraction column using ^{68}Ga in the form of gallium chloride from an industrial radionuclide generator (^{68}Ge/^{68}Ga). Labeling of water with the subject radiotracer in water-kerosene environment was evaluated. Experiments for Residence Time Distribution (RTD) analysis were carried out for a range of dispersed phase superficial velocities in a liquid-liquid extraction pulsed sieve plate column operating in the emulsion regime with water as continuous and kerosene as dispersed phase. Axial Dispersion Model (ADM) was used to simulate the hydrodynamic characteristics of continuous phase. It has been observed that the axial dispersion in the continuous phase decreases and slip velocity increases with increase in superficial velocity of dispersed phase while the holdup of continuous phase was found to decrease with increase in superficial velocity of dispersed phase. ADM with open-open boundary condition was found to be a suitable model for the subject system.

Keywords: *^{68}Ge/^{68}Ga generator, Residence Time Distribution (RTD), axial dispersion, holdup, slip velocity, pulsed sieve plate extraction column*

Development of $^{115}Cd/^{115m}In$ Generator for Industrial Applications

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Abstract

Indium isotopes, ^{111}In, ^{113m}In and ^{116m}In are widely used as radiotracers. ^{113m}In generators have been produced and can be found in the international market. However they are manufactured by only a few firms worldwide, valued at rather high prices and they are not always available for sale (they may be manufactured upon request). Hence it would be of interest to produce the equipment in the country in which it will be used, provided it can produce the parent nuclide. In principle this is possible in the case of Brazil. However if ^{113m}In is the choice, its parent ^{113}Sn must be generated in a nuclear reactor by neutron irradiation of the target nuclide ^{112}Sn, whose isotopic abundance is only 1%. Thus, to produce ^{113}Sn at high activity concentrations would be difficult considering the neutron fluxes available in the Brazilian reactors. In Brazil, the ideal situation would be to produce a generator that would use as target ^{114}Cd to produce ^{115}Cd. Preliminary tests using non-enriched and non-irradiated CdO have been developed. The separation of father and son nuclides have been done through the interaction of the chemical species Cd^{2+} and In^{3+} with ion exchange resins. The amount of Cd^{2+} and In^{3+} present in the eluent is determined by ICP-AES and atomic absorption. The resins were effective in the adsorption of Cd^{2+} in 2.0 $mol.L^{-1}$ HCl, which are used as eluent for In^{3+}. Experiments using enriched and irradiated CdO have been performed. For the tests with radioactive isotopes, analysis by gamma spectrometry has been performed to determine the purity and amount of In^{3+} present in the eluted fractions.

Extended Application of Radon as a Natural Tracer in Oil Reservoirs

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Abstract

Up to the 80´s it was a common practice in studying contamination by NAPL´s to incorporate a tracer to the medium to be studied. At that time the first applications focused on the use of Radon-222 (^{222}Rn), a naturally occurring radioactive isotope as a natural tracer, adequate for studies of thermodynamics, geology and transport properties in thermal reservoirs. The possibility of using radon to determine the residual oil saturation (SOR) derives from the fact that it is more soluble in oil than in water, being the two phases present in the reservoir. In 1993 the deficit of radon was used to spot and quantify the contamination by DNAPLs (Dense Nonaqueous Phase Liquids) under the surface. For the first time these studies showed that radon could be used as a tracer partition. A methodology is under development at CDTN that provides alternatives to quantify the oil volume stored in the porous space of oil reservoirs. The methodology applies, widens up and adapts the knowledge gained from the use of radon as a tracer to the studies aimed at assessing SOR. It is a postulation of this work that once known the radon partition coefficient between oil and water, SOR will be determined considering the increased amount of radon in the water phase as compared to the amount initially existent as the reservoir is flooded with water. Five main activities concur to support the development of this methodology:

1. Detailed information of the area to be studied by sampling water, oil and the porous medium.
2. Characterization of the porous medium to determine radon concentration, porosity and permeability, among other features.
3. Characterization of the fluid to determine, for example, densities, salinities and the partition coefficient between water and oil.
4. Carrying out bench tests, which involve the simulation of the processes of drainage and imbibitions.
5. Determination of SOR. The final phase of the development will soon be tested in the field.

For many years the SOR determination was only used for reservoir modeling and to predict its decline. Only in the 70´s the SOR knowledge started being used not only to mark the end point being reached during reservoir flooding with water but also became a reference point for recovery projects. The use of radon as a tracer in the oil industry may become an alternative method to allow a better assessment of the SOR during the reservoir lifetime, extending the possibilities of choice and comparison between the available methods for assessment of the reserve and thus a more realistic planning of the oil recovery schemes. This paper will present a description of the apparatus used and some preliminary results of the experiments.

Everything Goes Somewhere; Tracking the Movement of Contaminated Sediments in an Industrialised Estuary Using Dual Signature Sediment Tracers

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Abstract

Source control i.e. the reduction of contamination from upstream or diffuse sources, is a critical element in any management plan for contaminated waterways. If source control measures are not successfully implemented then a situation exists in which contamination will continue through time, and the cleanup of waterway segments becomes increasingly problematic. In order to understand more the issues surrounding source control, it is essential to have some understanding of contaminant sources and transport pathways of contaminated particulates. In port areas a plethora of factors interact to control contaminant transport pathways. These include: rain and river flow; tidal circulation, surface waves and wind drift, and temporally changing water column stratification. Particle tracking offers a practical means to map the transport pathways of contaminated sediments under these collective influences. This presentation aims to introduce the particle tracking technique through a study example in the Lower Duwamish Waterway, Washington, USA. Dual signature tracers were used, which possess both fluorescent colour and magnetic character in order that they may be unequivocally identified following release.

The presentation will describe the study from conception to results. The series of steps necessary to undertake such a study (including native sediment characterization, tracer specification and testing, tracer introduction and sampling, tracer enumeration) will be summarized. The principal findings of the project will be presented within the context of the Conceptual Site Model for the Lower Duwamish Estuary and the regional Sediment Transport Model.

Tracing of two-phase flow for diagnostic of industrial plate fin heat exchanger

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Abstract

If the tracing methods are commonly used for trouble shooting in industrial devices, they are mainly limited to qualitative determination of standard troubles (short-cut, dead volume…) and determination of Residence Time Distribution for a given phase. The aim of this work is to obtain a "tracing signature" in a new plate fin exchanger under multiphase flow conditions in order to be able to monitor its long term behaviour and to detect online accidental troubles. The objectives are to determine flow regime from signal characteristics (e.g.: bubble quantity and average void fraction) and the kind of technical troubles (fooling, fin damages…), the approximate locations and the degree of damage.

The major troubles occurring in plate fin heat exchanger are fouling of micro channels and damage of the fins, inducing flow maldistributions. The heat exchanger channels are several meter large and operate under multiphase flow conditions. In order to develop the methodology a special set-up has to be developed to measure local tracer responses and to link them with the global outlet response. Moreover the obtained signals need to be treated in order to discriminate information which characterize the flow regime from those linked to the residence time distribution inside the device.

The experimental loop consists in a vertical compact heat exchanger channel with a rectangular cross-section (dimensions 1m × 1m × 7.13mm). The investigated plate of fins is placed between two transparent acrylic glass plates to enable flow visualisation. The tracer (NaCl) is injected at the water inlet. The salt concentration is continuously measured across the heat exchanger outlet using a multi-channel conductivity probe developed in our laboratory.

The method has allowed the determination of the local residence time distribution of the liquid phase. The interpretation of the fluctuation of the signal due to the presence of gas bubble between the two electrodes of the conductivity proof has led to characterize the different flow regimes (bubbles, slug and churn), void fraction and the average bubble size. Different default detection and their level and location have been investigated.

This work has allowed to carry out a methodology for determination of location and level of several type troubles in a heat exchanger rectangular channel fed by multiphase flow. The next step will be to compare numerical RTD issued from Computational Fluid Dynamics simulations and those derived from tracer experiments. Simple compartmental models would be developed through the interpretation of tracer experiments and CFD simulations.

TRAC : a software for tracer test interpretations

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Abstract

Artificial tracer test are widely used by consulting engineers to demonstrate water circulation, prove the existence of leakage or estimate groundwater velocities. Interpretations of these tests are often very basic. Decision makers and professionals are frequently facing unreliable results leading to hasty and empirical interpretation. There is an increasing need for an interpretation tool, compatible with the latest operating systems, available in several languages. BRGM (French Geologic Survey) has developed a project together with hydrogeologist from various horizons to build a software assembling several analytical solutions in order to comply with various field context. This computer program, named TRAC, is very light and simple. It allows the user to add its own solution if the formula isn't included yet. It aims at a collaborative improvement by sharing the tool and the solutions.

TRAC may be used to interpret data recovered from a tracer test as well as simulate the transport of a tracer in the underground (in the saturated zone for the time being). Taking into account hydrodynamical and hydrodispersive features of the groundwater flow, the amount, nature and injection mode of the artificial tracer, allows to calibrate a site operation.

The software beta version was issued in January 2011. It is available in French, English and Spanish. The web site http://trac.brgm.fr offers to download the latest version.

Long term evolution of carbonate caprocks for geological carbon dioxide storage using tracer experiments

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Abstract

A short-term possibility to reduce atmospheric carbon dioxide concentration is the geological storage. To assess long-term safety of CO_2 storage sites, it is necessary to verify the stability of the confining properties of the caprocks and their evolutions in presence of salty water saturated in CO_2. Tracer experiments methodologies are very well adapted tools to measure diffusion coefficient of the major species involved in the storage and permeability of the caprocks before and after injection.

Long term safety of geological carbon dioxide storage site cannot be studied in real conditions for several reasons. Laboratory measurements require working with core samples, whose dimensions are far from the real size of the storage and certainly not fully representative of the average structure. The time scale of storage duration is some thousand years' order of magnitude, far from what can be done in laboratory. Finally pressure, temperature and chemical composition inside the reservoir are difficult to reproduce in a small laboratory set-up. Because of this, experimental set-up and operating conditions have been designed carefully in order to carry out short term measurements representative of long term alteration.

Experimental cells and set-up were designed to measure permeability and diffusion coefficient. Alteration procedures were developed in order to carry out tracer experiments before and after alteration. Permeability was obtained through a Helium tracer experiment. A strong originality is that diffusion coefficients were measured using radiotracers, THO and ^{14}C in order to estimate CO_2 and carbonate ions diffusions.

The results show that the studied caprocks strongly resisted to the acid alteration even under severe conditions. The permeability and the coefficient diffusion both for small (HTO) and larger molecules ($^{14}CO_3^-$) remain of the same order of magnitude before and after alteration. However, it has also been observed that the initial presence of sealed cracks in the samples could strongly enhance their deterioration and lead to permeability increases of orders of magnitude.

The study of caprock properties evolution during geological storage of carbon dioxide measured by different tracer techniques indicates a good resistance of the studied materials to alteration. From the more general point of view, this work points out the necessity to develop a methodology of short term measurement in a small sample to derive information on large scale structure for long term evolution. Tracer experiments interpretation need to be developed also to reduce time duration of experiments and to separate local phenomena due to initial heterogeneities in the sample from global diffusion process.

Tracer monitoring of Enhanced Oil Recovery (EOR) projects

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Abstract

To improve oil recovery, chemicals can be injected into the oil reservoir either to improve macroscopic sweep efficiency or to reduce remaining oil saturation in swept zones. Tracers can be used to identify reservoirs that are specifically suited for EOR operations. Injection of a selection of partitioning tracers, combined with frequent sample analysis of produced fluids, provides information suited for estimation of residual oil saturation.

Tracers can also be used to evaluate and optimize the application of EOR chemicals in the reservoir. Suitable tracers will follow the EOR chemicals and assist in evaluation of retention, degradation or trapping.

In addition to field applications, tracers also have a large potential as a tool to perform mechanistic studies of EOR chemicals in laboratory experiments. By labeling EOR chemicals with radioactive isotopes of elements such as H, C and S, detailed studies of transport mechanisms can be carried out. Co-injection of labeled compounds in dynamic flooding experiments in porous media will give information about retention or separation of the unique compounds constituting the chemical formulation. Separation of such compounds may be detrimental to obtain the EOR effect expected.

The paper will give new information of specific methods and discuss current status of use of tracers in EOR operations.

Injection Return Management: Results of Naphthalene Disulfonates tracer tests In Palinpinon-1 and its Implications to future resource development

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Abstract

Tracer test using Naphthalene Disulfonates (NDS) was conducted in the Palinpinon-1 sector of Southern Negros Geothermal Production Field. The test was designed with the following objectives: 1) to quantify the rate and extent of injection returns, 2) to identify fluid flow paths/channels of injection returns and 3) to predict thermal breakthrough or possible cooling of production wells due to injection returns. The results would help refine the hydrological model of Palinpinon-1, which would be the basis for prediction of reservoir response to increased mass extraction rate and brine injection load.

Three injection sectors were investigated: PN5RD-sector, Malaunay, and, Ticala sectors. Brine from these sector was traced using 2,7 NDS, 2,6 NDS, and, 1,5 NDS, respectively. Tracers were injected to dominant injector well in each sector. Based from the results, about 66% of wells were affected by injection returns. Tracer recovery in most of the wells arrived in 5 to 7 days after injection. Calculated tracer mass recovery ranged from various sector varies: well affected by Malaunay has about 42.6% mass recovered, while wells affected by Ticala and PN5RD averaged at 9.6% and, 6.7%, respectively.

Cooling predictions were conducted to simulate cooling of Ticala- affected wells from cold-condensate (55°C) injection. At highest load of condensate injection of 60 kg/s, temperature is expected to drop by 10 to 30°C in ten years operation. This is equivalent to decline rate 3 MWe/yr. However, cooling prediction of Malaunay-affected well at same injection temperature and load, the computed decline rate is minimal.

Keywords: *naphthalene disulfonates, tracer test, injection return, cooling predictions, Palinpinon*

The IAEA Activities on Radiotracer and Sealed Source Techniques for Industrial Applications

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Abstract
Radioisotope-based tracer and sealed source techniques have been widely used in industry for troubleshooting, analysis of industrial process to optimize process management, solving operational problems, improving product quality, saving energy and reducing pollution. The IAEA has been playing an important role in coordinating the knowledge generation in this field and facilitating transfer of the technology to interested developing countries. A number of coordinated research projects (CRP) and regional and national technical cooperation (TC) projects have been implementing for effective development and dissemination of the techniques. The recent R&D and TC activities in the field of radiotracer and sealed source techniques and the outputs of the activities are introduced. Some emerging industrial radioisotope techniques and the problems on the use of radioisotopes in industrial systems in developing countries are presented and the strategy to overcome the problems is discussed to suggest future activities among the industrial radiotracer society.

The role of tracer tests in geothermal resource management

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Abstract

Geothermal resources are distributed throughout the Earth's crust, ranging from volcanic hydrothermal systems to deep circulation systems in crystalline rocks and warm groundwater in sedimentary formations. Shallow thermal energy utilization through ground-source heat-pumps is also possible world-wide and experimental enhanced geothermal systems (EGS) are being developed in a few locations where limited permeability precludes natural hydrothermal activity. The potential of the Earth's geothermal resources is enormous and they have the potential of contributing significantly to sustainable development, both for electricity generation and various direct heat uses. Reinjection, which involves injecting energy-depleted fluid back into geothermal systems, is an essential part of their sustainable management. It started out as a method of waste-water disposal, but is now also used to provide supplementary fluid recharge, and to enhance thermal energy extraction. The possible cooling of production wells, or thermal breakthrough, is one of the main disadvantages associated with reinjection. Tracer testing has become a highly important tool in geothermal research, development and resource management. Its purpose is mainly threefold: (1) For general hydrological studies of subsurface flow, (2) for reinjection research and management, in particular to foresee the possible cooling of production wells due to long-term reinjection of colder fluid, and (3) for flow rate measurements in pipelines carrying two-phase water mixtures. Tracer testing has been most important in reinjection studies because it provides information on the nature and properties of connections, or flow-paths, between reinjection and production wells. In such situations tracer tests actually have a predictive power since tracer transport is several orders of magnitude faster than cold-front advancement around reinjection wells. This is what distinguishes tracer tests in geothermal applications from such tests in other disciplines. The main uncertainty in cooling predictions based on tracer tests arises from the fact that while tracer tests provide information on the volume of flow paths connecting wells, the cooling is determined by the surface area of the flow-paths. Comprehensive interpretation of geothermal tracer test data, and consequent modelling for management purposes, has been rather limited and tracer test interpretation has mostly been qualitative. A simple and efficient method of tracer test interpretation has been developed based on the assumption of specific flow channels connecting reinjection and production wells. It uses an inversion technique to simulate tracer return profiles, and to estimate the properties of the flow channels, which are consequently used for predicting the eventual production well cooling. Numerous examples are available for the successful application of tracer tests in geothermal systems, many involving the application of this interpretation technique, e.g. in several hydrothermal fields in Iceland, the USA, Japan, the Philippines and El Salvador as well as in the EGS-system at Soultz in France. The tracers most commonly used in geothermal applications are fluorescent dyes, chemical substances and radioactive isotopes. In two-phase situations both water-phase and steam-phase tracers must be applied. New temperature-resistant tracers have been introduced and high-tech tracers such as nanoparticles and quantum-dots are being considered. Tracer testing in the geothermal industry has been adopted from other disciplines and adjusted to the industry's specific needs. The geothermal industry also needs to follow and adopt relevant advances while other disciplines may of course also benefit from advances in geothermal tracer testing, such as concerning temperature tolerance.

Investigation of helical flow by using tracer technique

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Abstract

The flow through coiled tubes is, in practice, important for pipe systems, heat exchangers, chemical reactors, mixers of different gas components, etc., and is physically interesting because of the peculiar characteristics caused by the centrifugal force. Therefore, it is not so easy to observe flow parameters in the helical pipe experimentally. Tracer techniques are being increasingly used to determine characteristics such as volume flow rate, residence time, dispersion and mixing process in industry. In this study, the flow in the helical pipe was obtained in the laboratory and investigated by using the tracer technique. For the experimental system including the helical pipe was set up in the laboratory. In the experiments methylen-blue ($C_{16}H_{17}N_3S$) has been used as the tracer. The experiments were observed for the different flow rates successfully. Experimental results were evaluated with the flow parameters and the sensitivity of the method was obtained for different conditions.

Radiotracer Application at Dresden University and Fraunhofer Institute for Nondestructive Material Testing (Dresden)

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Abstract

In 1957, the Faculty of Nuclear Technology was founded at the Dresden University of Technology. One of the aims of this faculty was to develop methods of radiotracer usage and to apply these methods at technical scale. The group "Technical Isotope Application" performed a lot of measurements in industrial plants. This group worked under different names up to 2005. Since about 2000, some capabilities have been transferred to the Fraunhofer Institute of Non-Destructive Testing, Dresden branch. In the following, an overview is given on working fields or investigated equipments, resp.

1. Application and development of radionuclide generators

Radiotracer investigations are done preferably by using short-lived radionuclides. As in nuclear medicine, the application of radionuclide generators (Mo-99/Tc-99m and Sn113/ In113m) has advantages also in technological applications, especially the long usability of the generator system. For dedicated purposes, namely the investigation of high temperature processes, a new generator system (Ba-140/La-140) was developed and applied.

2. Work on further development of radiotracer

- In many papers, the momentum method was explored. This method has the advantage, that a residence time distribution is interpreted without any model assumptions. The mean residence time and other parameters are calculated only from statistical moments and applied to material transport processes.
- Activity estimation is an important part prior an investigation will be accepted by the radiation protection authorities. A computer program is developed based on the plant values and on the expected worst residence time distribution.
- During radiotracer measurements, the residual pulse density sometimes does not decrease to the original background. With the assumption, that the residual pulse density is caused by deposition of radioactive material near the detector, correction procedures were developed and used.

3. Working fields

Open radionuclides:

Residence time measurements in

- Water, waste water, filtration
- Gas exchange and reactions in gas phase; fluid beds
- Conveyers, dryers, rotary kilns, mills
- Plants for chemical fibres, polymers; in extruders and others
- Estimation of oil consumption of cumbustion engines
- Particle tracking in a screw conveyer by activated glass balls
- Investigation of mixing processes

Application of sealed sources

- Estimation of ash content and heat value of brown coal
- Estimation of sedimentation in a smoke channel of a thermal cracker
- Steam estimation in streaming hot water

An alternative approach to track a single radioactive particle inside a closed enclosure

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Abstract

In industrial production transport processes of granular media play an important role. The growing power of modern computer systems allowed the development of simulation programs mimicking transport devices and the processes there in on the scale of individual grains. However, at those calculations a verification with the real system usually cannot be done easily due to the very limited accessibility of the carried goods. In this contribution we want to show a CARPT-method capable to track individual particles in a mass stream inside a complicated worm transporter overcoming the need of a calibaration process by a meticulous calibration of the radiation detectors and a sophisticated analysis of the measured data using a simplified model of the transporter.

The CARPT method uses the effect that the count-rate in a radiation detector depends on the distance r of the source of the radiation to the detection device. At first, the count-rate decays by the r^{-2} law.When solid matter is in the pathway of the radiation, the intensity is attenuated further more due to absorption by this matter.This implies that the geometry of the setup must be known well and preferably analytically allowing that some kind of ray-tracing can be performed to get the path lengths though individual media spieces to calculate the count rates inside the detectors from a given position of the radiation source to the known positions of the detectors.

The CARPT procedure described here requires that all the detectors count exactly the rates received by the scintillation crystal. The raw count rates have to be corrected according to the dead-time of the detection system. The dead-times were obtained using the radioactive particles to be used for the CARPT experiment and trying to verify the r^{-2} law without any absorbing matter in-between the source and the detectors.

Using 12 scintillation detectors arranged in three planes around the transporter it was possible to locate the single particle and track its position with a spatial resolution of better than 1 cm and a temporal resolution of 200 ms.

In the investigated application, the data were used to distinguish different transport modes of the transporter depending on the filling level and their mixed variations. The power of the described CARPT method is the detection of even small variations of the mode material moves in the transporter. The limiting components of this approach are slow detection systems. When higher speed detectors will be available, this method will be applicable to large structures and/or fast moving flows.

Determination of the hydraulic residence time of two subsurface-flow constructed wetlands using radiotracers

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The adoption of constructed wetland systems (CW's) with subsuperficial drainage for sewage treatment is increasingly growing in places with low technological resources and available land. Cw'S have been used with good results in the treatment of solids in suspension, biological oxygen demand, bacteria (Escherichia Coli, faecal coliforms), and for the removal of nitrogen and metals from wastewaters. The efficient removal of pollutants depends on a favorable combination of chemical, biological and physical conditions. These are in turn rely on the internal flow characteristics in the CW and on its hydraulic residence time. Thus, preferential flow and short circuits may result in loss of efficiency of treatment. Evaluation of dispersion in a CW as well as the determination of preferential flows, stagnant and a active zones can be obtained from the distribution of residence times (RTD) within the system. In the present work a radiotracer was used: ^{82}Br, a gamma radiation emitter, produced in the TRIGA reactor at the Centre for the Development of Nuclear Energy. This pseudo-conservative tracer allowed the comparative study of the flow dynamics of the aqueous phase of two CW's, in one of which plants were grown (WP), whereas the other had no plants (WNP). Soluble irradiated potassium bromide has been used as a tracer of water flow. The 36 hours half-life of the radioisotope is suitable for this application, since it is the same order of magnitude of the calculated hydraulic detention time (HDT). The experimental average residence time parameter $(\bar{t})$ and the dispersion number (d) were obtained from the RTD centroid and variance, respectively. On the other hand the hydraulic efficiency was calculated taking into account the time at which the peak of the tracer concentration is detected and the average residence time. HDT values were found to be very close to the theoretical (1.47 days), amounting to 1.3 days in the WP and 1.43 days in the WNP. Thus, the volumetric efficiencies of the CW's were also were higher than the expected performance, due to an optimal utilization of their net storage volume (97% in the WNP vs. 89% in the WP). Dispersion numbers found for two CWs were also similar: 0.095 in the WP and 0.078 in the WNP, which are considered as moderate dispersion in the literature. The the number of tanks in series obtained for WP was 2.88 and for WNP was 3.78. The RTD curves of the tracer test and the measured hydrodynamic parameters demonstrate the tendency of the units to display a plug flow-like effluent hydraulic transport within their systems, as expected from their designs, considering the large length/width ratio (L / B = 8).

Preference: poster presentation

Design of a Tracer Based Monitoring Network to Support Monitoring Verification and Accounting of Sequestered CO_2

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Introduction: A brief overview of BNL tracer capabilities and research

The Tracer Technology Group at Brookhaven National Laboratory has developed methods for the use of perfluorocarbon compounds (PFTs) to the study of atmospheric transport on local, regional, and continental scales and in rural and urban environments. These techniques have been applied to the study of building air infiltration, the performance of HVAC systems in nuclear power plant control rooms, the effectiveness of building ventilation systems designed to protect occupants from releases of toxic chemical and biological agents, underground transport in soils, the integrity of subsurface hazardous waste containment structures, the study of dispersion of toxic materials in urban environments, and location of underground leaks. The Tracer Technology Group is now supporting renewable energy development by applying tracer methods to the quantitative characterization of temperature distributions and surface area available for heat transfer in Engineered Geothermal Systems (EGS). This presentation will briefly describe BNL tracer capabilities and applications of this technology in our ongoing research. The use of PFTs to EGS research will be emphasized.

The design of a Tracer Based Monitoring Network to Support Monitoring Verification and Accounting of Sequestered CO_2

There has been growth in CO_2 emissions since the beginning of the industrial revolution as population growth and global industrialization has kept the demand for energy growing – and this growth is accelerating. Stabilization of atmospheric levels of green house gases such as CO_2 will require a mix of strategies including increases in energy efficiency, a switch to energy sources that do not emit CO_2, and carbon capture and sequestration (CCS).

Geologic sequestration is permanent storage of captured CO_2 in depleted oil wells, unminable coal seams, and deep saline aquifers. This technology is most efficiently applied to large point sources such as coal fired power plants. A minimum of 90% reduction of CO_2 emissions from coal fueled power plants is required to stabilize atmospheric CO_2 levels. CCS will only be effective if the leak rate during transport or from the storage reservoir is less than 1%. Monitoring Verification and Accounting (MV&A) at sequestration sites is necessary to insure regulatory compliance, health and safety of local populations and ecosystems, and global environmental benefit of sequestration projects.

There are three levels of monitoring: subsurface using remote sensing and monitoring wells; near surface including soil gas analysis and measurements of ground water chemistry; and atmospheric monitoring, including direct measurement of CO_2, eddy correlation measurement of CO_2 fluxes, remote sensing, and measurement of tracers. There are significant challenges in direct monitoring of CO_2 because it requires the measurement of a small change in a large number. The CO_2 background is currently 380 ppm and growing at approximately 3% per year. The diurnal and seasonal variability of CO_2 are both on of the same order as the growth rate. A monitoring network must also cover an area on the surface above the sequestered CO_2 of 100 – 300 km2. The CO_2 plume from any leak will be diluted

during transport both below ground and once it reaches the atmosphere, making detection even more difficult. Tagging of the sequestered CO_2 with tracers can mitigate these problems.

The application of simple dispersion models to determine both subsurface and atmospheric concentration levels is necessary to develop the design criteria for a network of MV&A measurements of a CO_2 reservoir. The modeling results will be used to develop a subsurface and atmospheric sampling plan. The plan will include tracer tagging levels, sampling methods, sampling density, and a sample analysis strategy. The role of climatology, wind direction probabilities, and stability class frequency will be examined. The requirements for reservoir leak rates of 1%, 0.01%, 0.001% year-1 will be presented. Problems with the use of PFTs for MV&A including the atmospheric lifetime, green house warming potential, and the effects of PFT solubility in hydrocarbons will be discussed.

Conclusions will include recommendations for the design of the surface and subsurface sequestration monitoring network. The justification for local meteorological monitoring, a passive sample network design, and a sample analysis strategy will be presented. The importance of implementation of a global monitoring program for tracking PFT background levels will be emphasized.

Tracers in oil fields: the Argentinean experience

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Applications of tracers in interwell studies started in Argentina in 1978 when the first experience in a Latin American oil field was carried out. Since that time up to the present more than 200 experiences were performed in many different oil fields belonging to several companies.

Tritiated water was the tracer used in most of the applications and the only one really liable in the first years but as time went by other tracers were also added to the box tool. Ammonium thiocyanate, alcohols, acid yellow as a die and, more recently, fluorinated benzoic acids were included to the offer whenever multi trace was needed. In this presentation some examples of the use of different tracers is shown as well as a comparison of the advantages, disadvantages and main characteristics of each of them from the point of view of their application in Argentine basins.

As basic tools for primary interpretation or simulation, Anduril software was developed by Noldor S.R.L. and PORO software was developed by Comahue University. Here, some examples of the use of both of them together are discussed after a brief explanation on their operation principle and use.

Hydraulic fracture constitutes another field of application of tracers, especially when multiple fractures take place in the same well. If a portion of the gel used during the fracturing process is retained by the fractured zone, the oil production may be affected. In such a case, the role of multiple tracing of that gel is extremely important when the flow back of each fracture is analyzed in order to know if all the gel that was injected at different depths is coming back. As a support for these tasks, POROfrac software is now under developing in Comahue University being its main purpose to simulate the behavior of a tracer during the fracture operation (a beta version is available). Some examples are presented here.

Finally, another problem to be taken into account in the oil industry, in this case when a new well is drilled is the invasion of the formation with drilling mud. The main consequence of this process is the displacement of the original fluids inside the reservoir creating a flushed zone around the well. Because of the invasion of drilling mud, the identification of productive zones may result more difficult and the evaluation of reserves not so reliable. Tagging the drilling mud with a small activity of tritiated water and taking samples from the cores at different depths make it possible to establish a profile of mud invasion and to correct the values of resistivity, water saturation and other parameters with the main goal of obtaining more accurate results. Examples are also discussed.

Radioactive Labelling of Surfactants for Use as Tracers in EOR Methods

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Abstract

In a project at the Institute for Energy Technology (IFE) it was desirable to study mechanisms for the use of surfactants in combination with supercritical CO_2 for enhanced recovery of residual oil from mature oil reservoirs. Foam by surfactant, CO_2 and water were suggested as a possible tertiary method for enhanced oil recovery (EOR). It was desirable to synthesize radioactively labelled surfactants, which first were to be used in simulated reservoir experiments in the laboratory. By labelling surfactants radioactively, a very good detection is achieved.

Two aliphatic sulfonic acids were chosen as targets for a synthesis: 2-dodecene-1-sulfonic acid and 3-hydroxy-dodecane-1-sulfonic acid. Since the surfactant molecule contained a sulfonic acid group, it was decided to label the molecule with ^{35}S. In this study only the synthesis, separation and analysis of the products and by-products will be looked at.

For the synthesis of sulfonic acids, acetyl sulfate was formed from the reaction between acetic anhydride and fuming sulfuric acid (sulfuric acid with 20% SO_3). ^{35}S-H_2SO_4 was added to the radioactive synthesis. According to the literature the sulfonation can be done with both acetyl sulfate and sulfur trioxide in reaction with the alkene. In this study, 1-dodecene was used as the alkene. Synthesis gave the products that were the aim, but also 1-dodecene-1-sulfonic acid. Some minor products were also formed, but not characterized because of the small amounts. Somewhat unexpectedly sultones was not seen among by-products.

Sulfonic acids were separated on a preparative column and fractions analysed by liquid scintillation counting (LSC) and HPLC. The method of separation was reproducible and gave a good separation of the different sulfonic acids. The separation gave pure fractions that could be used further in the simulated reservoir experiments in the laboratory. The same method of synthesis and separation was performed without ^{35}S-H_2SO_4. Fractions were combined after analysis on HPLC and the different sulfonic acids were characterized with ^{1}H-NMR and MS.

An attempt on a different separation method where larger amounts could be separated was done with a weak anionic exchange column. But the sulfonic acids were not separated. It was concluded that this method requires more development.

Quantitative Inflow Interpretation of RESMAN Intelligent Tracers in a Multilateral Well

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Abstract
RESMAN is developing a new technology that measure wirelessly the downhole production profile and have now several case histories that show the potential of the technology. The basic theory involves both chemistry and flow technology. The core technology areas include release of tracers into target fluid and transportation with the target fluid to a topside sampling point for analysis. Tracers have been used for marking of target fluid for many years, but RESMAN is now offering quantitative inflow assessment.

This case is from a multilateral well which illustrates the power of RESMAN Intelligent Tracers to provide significant insight into the inflow distribution along each lateral well. From knowledge about production rates together with the given tracer responses, RESMAN can indicate which section of the well that is the major contributor in both laterals. As the life length of the RESMAN intelligent Tracers are increasing, this type of analysis can be repeated as frequently as desired over several years without any intervention into the well.

The value of repeated tracer injections in subsurface flow examinations

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Abstract

The flow patterns in subsurface reservoirs may change significantly during time. Especially in fractured reservoirs with long horizontals wells, rapid breakthrough of water can occur in zones of the well and new zones may start to leak during time. Identifying such shortcuts is of great importance for reservoir management and if intelligent completion (e.g. sliding sleeves doors) is in place, the short-cutting water can easily by shut off.

This presentation will show field examples from an oil reservoir. Also the importance of setting up a good sampling program to be able to quantify the leak will be discussed.

Status of the development of radiotracer generators for industrial use, - the IAEA approach

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Abstract

Short-lived gamma-emitting radionuclides, in some cases coupled to a carrier molecule in an organometallic compound or as a chemical complex, offer unique possibilities as tracers for non-intrusive examinations of mass transport operations in industrial process vessels. However, until recently, the use of this method has been limited to regions in relatively close vicinity of a production facility like a nuclear reactor, a neutron generator or a particle accelerator. The last 3-4 years has seen a focus on technical development to overcome this limitation by R&D programs to develop so-called radiotracer generators.

Short-lived radionuclides may be obtained from radionuclide generators based on nuclear mother-daughter relationships. We report here on experiments performed, partly in a recent IAEA CRP, to utilize the short- lived radionuclides directly as tracers or indirectly as labels on carrier molecules for single phase and multiphase studies where the phases may be organic, aqueous or solid. Gas tracing is not considered.

The radionuclide generators originally selected for consideration are listed in the table below. The criteria was to cover a range of half-lives, various gamma energies, in some cases multiple strong gammas from the same radionuclide and possibilities to utilize radiotracers for positron emission tomography. During the experimental work it turned out that most emphasis were put on those colored green, some activity was reported on the light blue, minor activity on the grey and no activity on the purple.

Table: Potential radionuclide generators for industrial radiotracer applications

Radionuclide Generator	*Parent Nuclides*				*Daughter Nuclides*			
	Production	*Half-life*	*Decay*	*γ, keV*	*Half-life*	*Decay*	*γ, keV*	*Applications**
^{68}Ge/^{68}Ga	^{69}Ga(p,2n)^{68}Ge	270 d	EC	-	1.135 h	β^+	511, 1077	①-⑤, ⑥-⑦
^{137}Cs/^{137m}Ba	Fission product	30.0 a	β^-	-	2.55 min	γ (IT)	661	①-④, ⑨
^{113}Sn/^{113m}In	^{Nat}In(p,xn)^{113}Sn	115.1 d	EC	-	1.657 h	γ (IT)	391.7	①-⑤, ⑦-⑨
^{144}Ce/^{144}Pr	Fission product	285 d	β^-	133	17.3 min	γ	696	①-⑤, ⑨
^{44}Ti/^{44}Sc	^{45}Sc(p,2n)^{44}Ti	47.3 a	EC	67, 78	3.93 h	β^+	511, 1157	①-⑤, ⑥-⑦
^{99}Mo/^{99m}Tc	Fission product	66.0 h	β^-	739.4	6.0 h	γ (IT)	140	①-⑤, ⑨
^{172}Hf/^{172}Lu	^{173}Ta(p,2n)^{172}Hf	1.87 a	EC	24, 125	6.7 d	γ	1093	①-⑤, ⑦-⑧

**: ① Flow rate measurement, ② Residence time distribution measurement, ③ Leak detection and location, ④ Mixing study, ⑤ Mass balance, ⑥ Positron emission tomography, ⑦ Single particle tracing, ⑧ Sediment transport study, ⑨ Decay education*

NORWAY - Brief history Two centuries of Viking raids into Europe tapered off following the adoption of Christianity by King Olav TRYGGVASON in 994. Conversion of the Norwegian kingdom occurred over the next several decades. In 1397, Norway was absorbed into a union with Denmark that lasted more than four centuries. In 1814, Norwegians resisted the cession of their country to Sweden and adopted a new constitution. Sweden then invaded Norway but agreed to let Norway keep its constitution in return for accepting the union under a Swedish king. Rising nationalism throughout the 19th century led to a 1905 referendum granting Norway independence. Although Norway remained neutral in World War I, it suffered heavy losses to its shipping. Norway proclaimed its neutrality at the outset of World War II, but was nonetheless occupied for five years by Nazi Germany (1940-45). In 1949, neutrality was abandoned and Norway became a member of NATO. Discovery of oil and gas in adjacent waters in the late 1960s boosted Norway's economic fortunes. In referenda held in 1972 and 1994, Norway rejected joining the EU. Key domestic issues include immigration and integration of ethnic minorities, maintaining the country's extensive social safety net with an aging population, and preserving economic competitiveness.

Facts

Population 4,691,849 (July 2011 est.)

Area
- 323,802 sq km

Coastline
- 25,148 km (includes mainland 2,650 km, as well as long fjords, numerous small islands, and minor indentations 22,498 km;
- Length of island coastlines 58,133 km)

Natural resources
- Petroleum, natural gas
- Metals (iron ore, aluminium, copper, lead, zinc, titanium, pyrites, nickel, cobalt, niob, tantalum, thorium, REE)
- Fish
- Thimber
- Hydropower

Land
- Arable land: 2.7%
- Permanent crops: 0%
- Other: 97.3%
- Two-thirds mountains
- Some 50,000 islands

Population age structure
- 0-14 years: 18%
- 15-64 years: 66%
- 65 years and over: 16%

Life expectancy
- total population: 80.2 years

Total fertility rate
- 1.77 children born/woman

Ethnic groups
- Norwegian 94.4% (includes Sami, about 60,000)
- Other European 3.6%
- Other 2%

Religions
- Church of Norway 85.7%
- Pentecostal 1%
- Roman Catholic 1%
- Other Christian 2.4%
- Muslim 1.8%
- Other 8.1%

Literacy
- 100% age 15 and over can read and write

Government type
- Constitutional monarchy

Capital
- Oslo
- Population : 600.000

Economy
- GDP growth rate 1.5%
- GDP per capita $59,100
- Unemployment rate 3.6%
- Inflation rate 2.4%

Flag