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Abstract

Use of radioactive tracers for flow velocity measurements is well developed and documented. Measurement techniques involving pulsed sources of fast (14 MeV) neutrons for in-situ production of tracers can be considered as extensions of the old methods. Improvements offered by these Pulsed Neutron Activation (PNA) techniques over conventional radioisotope techniques are (1) non-intrusion into the system, (2) easier introduction and better mixing of the tracer, and (3) no requirement to handle large amounts of relatively long lived radioactive materials. Just as in conventional tracer techniques, flow velocity measurements by PNA methods can be based on the transit-time or the total-count method. A very significant difference of the PNA technique from conventional methods is that the induced activity is proportional to the density of the fluid, and that PNA techniques can be used for density measurements (of two-phase flows) in addition to flow velocity measurement. Original equations were derived that relate experimental data to the mass flow velocity and the average density. The accuracy of these equations is not effected by the flow regime. Experimental results are presented for tests performed on liquid sodium loops, on air-water loops, on the EBR-II reactor and on the LOFT reactor. Current instrumentation development programs (detectors, pulsed neutron sources) are discussed.

Introduction

The use of tracers for the study of various aspects of fluid flow goes back to the beginning of this century, when filaments of dye were used to visualize flow patterns in transparent pipes and open channels. Allan and Taylor¹ were among the first researchers to inject salt into water mains and to determine the flow velocity of the water from the time of arrival of the salt at a detector located downstream of the injection point. Hull and Kent² used radioactive tracers to measure flow velocities in oil pipelines. Several good surveys of the various methods used today are available.^{3,4,5,6,7}

Injection of tracers is done either continuously or at discrete times, and flow velocities can be measured from the dilution of the tracer concentration or from the average transit-time of the tracer from the point of injection to the point of detection. The equation used for the transit-time method is

$$Q = \frac{V}{\bar{T}}, \text{ where} \quad (1)$$

V = Volume (of the vessel or pipe) between the injection plane and the detection plane, and

$\bar{T}$ = Average transit-time (between the injection plane and the detection plane), or average residence time (in the vessel or pipe).

Short lived tracers can be produced in-situ by irradiating the fluid with neutrons. Neutron sources with continuous output as well as pulsed neutron sources can be used.

A large number of studies (including the classical work by Taylor^{8,9}), deals with the dispersion of the injected tracers in time, and with numerical methods for the derivation of an "average transit-time" suitable for use in Eq. 1. These methods derive an average transit-time $\bar{T}$ from the time distributed number of counts $C(t)$, by using the mode, the median, or the mean $\bar{T}$, where

$$\bar{T} = \frac{\int_0^{\infty} t C(t) dt}{\int_0^{\infty} C(t) dt} \quad (2)$$

J. I. Sackett (Argonne National Laboratory private communications, June 1971) has proposed that the count-weighted mean of the reciprocal of the transit-time, $(1/T)'$, be used as a measure for $1/\bar{T}$, where

$$\left(\frac{1}{T}\right)' = \frac{\int_0^{\infty} \left(\frac{1}{t}\right) C(t) dt}{\int_0^{\infty} C(t) dt} \quad (3)$$

It should be pointed out that $C(t)$ in the Eqs. 2 and 3 is the decay corrected number of counts per time channel, which is related to the (background corrected) measured number of counts, $c(t)$, as

$$C(t) = c(t) e^{\lambda t}, \text{ where} \quad (4)$$

λ = Decay constant and,

t = Time after irradiation of the fluid.

An urgent need exists in reactor research for the measurement of the mass flow of sodium, water, and steam-water mixtures. The feasibility of Pulsed Neutron Activation (PNA) techniques for the measurement of liquid sodium flow was studied at ANL¹⁰, and it was found that the transit-time method of the PNA technique was best suited for this application. We have then applied the transit-time method to the measurement of two-phase flow (air-water, steam-water). The success of our experiment is, basically, attributable to the availability of a very compact and portable neutron source developed by the Sandia Laboratories for a classified program not related to our work.

Equipment

For the measurement of mass flow velocities in pipes, a pulsed neutron source is positioned close to the pipe and the fluid opposite the source is activated by a short burst of neutrons (see Fig. 1). Ideally, the induced activity is originally confined to a narrow slice dZ , and distributed uniformly over the cross section of the pipe. However, the original distribution of activity is changed as the activated fluid moves down the pipe, and a detector located downstream of the pipe will register a distribution of counts as the activated fluid moves past it. Conventionally, the average mass flow velocity is then determined by deriving an average transit time for the activated slug of fluid, according to Eq. 1. Assuming that the cross sectional area of the pipe is constant over the whole length Z_0 , both the flowrate of the fluid, Q , and the volume of the pipe, V , can be expressed by the cross sectional area F , as $Q = U_M F$, and $V = Z_0 F$, where U_M = Mass flow velocity. Then, Eq. 1 becomes

$$U_M = Z_0 \frac{1}{\bar{T}} \quad (5)$$

Sandia developed neutron sources, Model TC655, were used in our work. These sources are of cylindrical form, have a diameter of 20 cm and are 35 cm long. They weigh 11 kg. Their neutron output is 3×10^9 neutrons/pulse. In experiments of long duration, we pulsed these sources once per minute. Under such conditions, the neutron output remained stable over 400 pulses. We have also pulsed these sources a few times allowing for recovery time of only 15 sec. The only equipment necessary for the operation of these sources is a 28 VDC, 5A power supply, which makes the whole system easily portable. The pulse duration of the source is classified, but the neutron burst can be considered to be infinitely short when compared with 1 m sec, the order of magnitude of the window width of multiscalers used in PNA tests.

Fig. 1 PNA Measurement Setup

Nuclear Reactions Utilized

The neutrons produced by the pulsed sources used in our measurements are of the $D(T,n)\alpha$ type with an energy of $E = 14$ MeV, and are very effective for a activation of water as well as sodium. For the activation of water, the reaction $O^{16}(n,p)N^{16}$ is utilized, which results in a radioactive nitrogen isotope that decays with a half life of $T_{1/2} = 7.2$ sec under emission of a gamma ray with an energy of $E_\gamma = 6.1$ MeV.¹¹ The cross section for the (n,p) reaction is 42 mb, and the threshold is 10.2 MeV.

Several reactions are possible for 14 MeV neutrons with sodium.¹¹ The reaction $Na^{23}(n,\alpha)F^{23}$ has the highest cross section and the shortest half life of the resulting radioisotope. Therefore, it is this reaction that can be best used for the measurement of liquid sodium flow velocities. The gamma rays produced by this reaction, having energies of $E_\gamma = 1.6$ MeV, must be discriminated from the gamma rays produced by thermal neutron capture in sodium, which have an energy of 2.75 MeV.

Analytic Modeling

In our early measurements, we have used Eq. 3 for the calculation of the average transit-time. This equation, although accurate for conditions where the counts are nearly normally distributed, was found to be inaccurate for application to two-phase flow conditions. In annular flows, for example, the liquid ring close to the pipe wall flows much slower than the mass at the center line of the pipe. In many situations, there is a distinct separation of the velocities of the two phases and the concept of "slip" can be used. For these complex two-phase flow conditions, a new set of two primary PNA equations was derived that describes accurately the mass flow velocity and the density of two-phase flows in terms measurable by PNA

equipment.

Primary PNA Equations

These PNA equations, derived below for two-phase flow conditions but equally valid for single-phase flows, measure independently the average mass flow velocity and the density of fluids. In contrast to conventional two-phase flow measuring system, which measure local velocities and densities, PNA techniques measure "global" velocities and densities and are not affected by specific characteristic of the flow regime or the flow profile. In two-phase flows, velocities and densities can change along the length of test section and can be described as in Fig. 2, where U_{LS} and U_{GS} are the superficial velocities of the liquid and the gas (with densities of ρ_L and ρ_G), U_{MS} is the superficial mass flow velocity (the sum of the liquid and the gas flow), U_S , ρ_S and U_D , ρ_D are the velocities and densities at the source location and the detector location, and U_T , ρ_T are the "transit" velocity and "transit" density, i.e., the velocity and density averaged over the length of the test section between the source and the detector.

Fig. 2 PNA Nomenclature

Now, the first of the two primary PNA equations relates the measured count/time distribution (such as illustrated in the multiscaler display at Fig. 1), to the true mass flow velocity of liquids in pipes, averaged over the volume of the pipe between the source and the detector locations. This equation is directly traceable to the definition of the average mass flow velocity, which is

$$\bar{U}_T = \frac{\sum U_T m(T)}{\sum m(T)}, \quad (6)$$

where

$m(T)$ = The mass flow past the detector at time t ,

U_T = The velocity of the mass $m(t)$, derived from the transit time T , and

$\bar{U}_T$ = The mass averaged (transit-time) velocity.

In Eq. 6, the transit-time T is equal to the "time" t , since the time sweep of the multiscaler is started at the time of triggering the neutron source.

Assuming that the neutron fluence over the cross section of the pipe is constant, then the activity $a(T)$ introduced into $m(T)$ by activation is related to the total activity, A , introduced into the total mass, M contained in dZ (see Fig. 1) as

$$\frac{a(T)}{m(T)} = \frac{A}{M} = \frac{A_0}{M_0}, \quad (7)$$

where

M_0 = The mass contained in dZ when the pipe is waterfilled, and

A_0 = The activity induced in M_0 by neutron activation.

Thus,

$$m(T) = a(T) \frac{M_0}{A_0} \quad (8)$$

Now, when the activity $a(T)$ passes the detector window ΔZ with a velocity U_D , (see Figs. 1,2), it will deposit a number of counts $C(T)$ that is proportional to this activity and inversely proportional to its velocity:

$$C(T) = \frac{C_0 U_0}{A_0} \frac{a(T)}{U_D} \quad (9)$$

where

C_0 = The number of counts registered by the detector when A_0 passes the detector window with a velocity of $U_0 = 1$ m sec.

Substitution of Eq. 9 for $a(T)$ in Eq. 8 leads to

$$m(T) = \frac{M_0}{C_0 U_0} U_D C(T) \quad (10)$$

and Eq. 6 reads

$$\bar{U}_T = \frac{\sum U_T U_D C(T)}{\sum U_D C(T)} \quad (11)$$

The velocity U_D across the detector window ΔZ is not known. However, if care is taken to assure that the flow over the whole test length Z_0 is constant, then the flow velocities at the detector, the source, and over Z_0 can be assumed to be identical, or

$$U_D = U_T = Z_0/T \quad (12)$$

and Eq. 11 becomes

$$\bar{U}_T = Z_0 \frac{\sum \frac{1}{T^2} C(T)}{\sum \frac{1}{T} C(T)} \quad (13)$$

Discussion of the validity of the assumptions made in deriving Eq. 12 as well as detailed demonstrations that Eq. 12 indeed measures the true mass flow velocity, independent of variations of flow regimes, is given in other publications.^{12,13}

The second primary PNA equation expresses the density of the fluid in terms of measurable activities. It is derived by equating the total activity injected by the neutron burst to the total activity detected by the detector, as shown below.

In two-phase flow, the density, ρ , and the mass M , contained in the source window dZ (see Fig. 1) are related through the volume V_S subtended by the neutron beam as $M = V_S \rho$, and the amount of activity injected into the fluid by a neutron pulse, A_S , can be expressed as

$$A_S = \frac{\rho}{\rho_0} A_0 \quad (14)$$

On the other hand, the total activity passing the detector, A_D , is

$$A_D = \sum a(T) \quad (15)$$

Using Eq. 9 for $a(T)$ and equating the two activities A_S and A_D leads to

$$\frac{\rho}{\rho_0} A_0 = \frac{A_0}{C_0 U_0} \sum U_D C(T) \quad (16)$$

In past work, it was found convenient to describe the parameters of a particular PNA setup by a constant K ,

$$K = \frac{C_0 U_0}{\rho_0} \quad (17)$$

This K -value describes the source strength and source collimation, detector size and detector collimation, discriminator setting, pipe diameter and all other details of an experiment. It is determined by measuring the total number of counts, C_0 , for a water-filled pipe ($\rho_0 = 1$) and a flow velocity of $U_0 = 1$ m/sec. Using the definition for K , Eq. 16 becomes (with Eq. 12)

$$\rho = \frac{Z_0}{K} \sum \frac{1}{T} C(T) \quad (18)$$

This equation, then, is a measure for the density of a steam-water mixture in a pipe, available by evaluating the counts/time distribution of a PNA test.

Secondary PNA Equations

Besides of the two primary PNA equations derived above, two secondary equations were found to be very useful for PNA data reduction. One is the well known equation relating the total number of counts to the flow velocity, which is simply derived by substituting general values $C = \sum C(T)$, U , and ρ , for the specific values C_0 , U_0 and ρ_0 in Eq. 17.

$$\bar{U} = \frac{K\rho}{\sum C(T)} \quad (19)$$

The physical meaning of the average velocity $\bar{U}$ can be understood by deriving Eq. 19 from Eq. 5, with a definition for the average transit-time as in Eq. 3. A second, independent determination of the density can be obtained by PNA methods to verify the measurement done by Eq. 18, whenever measurement of the superficial gas and liquid flow velocities are available. From these two superficial velocities, a superficial mass flow velocity U_{MS} can be calculated¹³ (see Fig. 2), and the density of the fluid ρ_T , averaged over the length Z_0 of the test section, is then calculated from the measured transit-time velocity $\bar{U}_T$ (Eq. 13) by

$$\rho_T = \rho_0 \frac{U_{MS}}{\bar{U}_T} \quad (20)$$

Experimental Data

Measurements at the EBR-II

Power calculations performed from data taken on the primary and the secondary loops of the Experimental Breeder Reactor-II (EBR-II) in Idaho Falls have shown a 9% discrepancy.¹⁴ To resolve this discrepancy, PNA measurements were performed on the secondary sodium loop of the reactor, which has a diameter of 30 cm. Our experiments have shown^{15,16} that, at full flow, the actual secondary flow is 1.057 times higher than the flow indicated by the permanently installed flow instrumentation. The discrepancy existing between primary and secondary loop power levels is now only 4%, and at full power operating conditions, the plant power is now calculated at 60.1 MWt.

The water flowrate in the EBR-II evaporator-downcomer was also measured by PNA techniques.^{16,17} Although the PNA measurement at the EBR-II were made

in a relatively high radiation background (due to the activation of sodium by thermal neutrons), the accuracy of the flow measurements was still about 1%. The agreement between predicted counting rates and measured counting rates was good.¹⁵

Measurements at the ETEC

The performance of the large sodium pumps of the Fast Flux Test Facility (FFTF) is being evaluated at the Energy Technology Engineering Center (ETEC) at Canoga Park, California. The permanent magnet flowmeters installed on the 40 cm pipes of the Sodium Pump Test Facility (SPTF) at the ETEC is routinely calibrated by readings from a venturi flowmeter installed in the same line. The venturi flowmeter, in turn, is calibrated in a water loop with known flow-rates. Since removal and re-installation of the venturi meter is cumbersome and costly, PNA flow measurements were made and compared with venturi meter readings. Test data (Fig. 3) have shown that PNA data are as accurate as the venturi data.¹⁸ It was decided, therefore, to install a PNA measuring system at the SPTF for routine calibration of the permanent magnet flowmeter.

Fig. 3 PNA Calibration of the Flowmeter at the ETEC

Measurements at the Semiscale Water Loop

Our first two-phase flow measurements were performed at the air-water loop located at the Semiscale facility at the Idaho National Engineering Laboratory (INEL) in Idaho Falls. Tests were performed at two pipe diameters, 7.5 cm and 12.5 cm, and for two source-detector spacings. Evaluation of test data has shown¹³ that, for the short spacings, there is good agreement between the transit-time velocity and the total-count velocity (see Fig. 4), as well as between the transit-time density and the total-activity density (see Fig. 5). Data derived by Eqs. 13, 18, 19 and 20 were used in these two figures. For the long spacings, the agreement between the two sets of velocity and density measurements were not good, due to the change of pressure along the test section. This pressure drop (due primarily to the instrument spool piece installed between the two detectors as well as to other causes) violates the PNA condition shown in Eq. 12.

Fig. 4 Comparison of Total Count-Velocities, U_{MC} , to Transit-Time Velocities, U_{MT}

Fig. 5 Comparison of Local Density, ρ , to Transit-Density ρ_T

Measurements at the LOFT Reactor

The Loss of Fluid Test (LOFT) facility, located at INEL, is a scale model of a Pressurized Water Reactor (PWR), designed to study the nuclear, thermal and hydraulic phenomenon which would take place in a PWR during a Loss of Coolant Accident (LOCA).

In its present configuration, the LOFT facility is capable of fulfilling a number of test objectives, including the study of Emergency Core Cooling Systems (ECCS's) used as safeguards in events of coolant loss, to remove heat from the core and to prevent damage to the fuel. PNA techniques were used to measure the relative ECC bypass flow at the LOFT reactor.¹⁹ Four simultaneously triggered neutron sources were used in this test and pairs of 12.5 cm diameter x 7.5 cm NaI detectors were used for the registration of counts. The experimental setup of the PNA equipment is illustrated in Fig. 6. The bypass ratio was found to be $(41 \pm 7)\%$.

Fig. 6 PNA Setup at the LOFT Reactor

Development of Neutron Source

A high-output neutron source is being developed by the Sandia Laboratories for future two-phase flow measurement by PNA techniques. Sandia has an established capability not only in the development and construction of classified neutron sources, but also of an unclassified neutron generator for use in uranium logging.²⁰ This unclassified logging generator uses a modification of the Controllatron, a General Electric - developed Penning ion source.²¹ Another type of ion source considered for incorporation in a two-phase measuring neutron source is a solid-state spark ion source originally developed at Berkeley.²² At the present time, Sandia has three different neutron source configurations under consideration. All three are likely to lead to a pulsed neutron source that will meet the requirements for our two-phase flow measurement program. The first approach utilizes the Berkeley-type, solid-state spark ion source, and a high voltage supply consisting of a transformer assembly and a pulse forming network (PFN). The second configuration under study is a Penning-type gas discharge ion source, again in combination with a PFN and a transformer assembly. The third neutron source under study uses a Penning-type ion source with a dc high voltage supply (a Cockroft-Walton generator). Pulsing of this neutron generator is achieved by pulsing of the ion source. Within the next few months, one of these three configurations will be selected for production. A prototype of the new pulsed neutron source will be available in mid-1980. The specifications for this unclassified source are: output: 10^{10} neutrons/pulse, pulse length: 1 m sec, recovery time: 5 sec, lifetime: 1000 pulses.

Development of Torus Detector

A torus detector, fully encircling a pipe, is being developed at ANL and will be available early in 1979. This detector will encircle pipes with diameters of 15 cm, will be 10 cm wide and will have a height of 8 cm. Four photomultiplier tubes will be used to detect the scintillations in the four-segmented NaI scintillator.

References

1. C.M. Allen and E.A. Taylor, Trans. ASME **45**, 285 (1923).
2. D.E. Hull and J.W. Kent, Industrial Eng. Chem. **44**, 2745 (1952).
3. K. Lijunggren, "Review of the Use of Radioactive Tracers for Evaluating Parameters Pertaining to the Flow of Material in Plant and Natural Systems", Intern. Atomic Energy Agency Proceedings, Radio-

References (contd.)

- isotope Tracers in Industry and Geophysics, Prague, (1966).
4. C.G. Claytorn, et.al., "The Accuracy and Precision of Liquid Flow Measurement by Radioactive Isotopes", IAEA Proceedings, Radioisotope Tracers in Industry and Geophysics, Prague (1966).
5. R.H. Lafferty, Jr., "Flow Measurement with Radioisotopes", Isotopes and Radiation Technology **8**, 3, 287 (1971).
6. A.E. Uhl, "Tracer Metering of Compressible Fluids", First Symposium on Flow, its Measurement and Control, ISA, p. 809 (1974).
7. A.R. Boswell, T.B. Pierce, "Flowrate Determination by Neutron Activation Analysis", Modern Developments in Flow Measurement, PPL Conf. Publ. **10**, p. 264, (September 1971).
8. G. Taylor, "Dispersion of Soluble Matter in Solvent Flowing Slowly Through a Tube", Proc. Roy. Soc. **219A**, 186 (1953).
9. G. Taylor, "The Dispersion of Matter in Turbulent Flow Through a Pipe", Proc. Roy. Soc. **223A**, 446 (1954).
10. Paul Kehler, "Feasibility of Calibration of Liquid Sodium Flowmeters by Neutron Activation Techniques", ANL-CT-76-17, (July 1976).
11. S.S. Nargolwalla and E.P. Przybylowicz, "Activation Analysis with Neutron Generators", Vol. 39 of Chemical Analysis Series, John Wiley and Sons (1973).
12. Paul Kehler, "Two-Phase Flow Measurement by Pulsed Neutron Activation Techniques", Paper to be presented at the ASME Winter Annual Meeting in San Francisco (December 1978).
13. Paul Kehler, "Two-Phase Flow Measurement by Pulsed Neutron Activation Techniques", ANL-NUREG-CT-78-17 (1978).
14. C.H. Golden, A. Goyala Kushman, R.A. Laskiewicz, "Correlation and Interpretation of Data Relative to EBR-II Power Level", Proc. Irradiation Experiments in Fast Reactors, 314-332, (September 1973).
15. Paul Kehler, C.C. Price, G.A. Forster, J.I. Sackett and R.N. Curran, "Measurement of Liquid Sodium Flow in the Secondary System of EBR-II by a Neutron Activation Technique", ANL-CT-77-25, (June 1977).
15. C.C. Price, J.I. Sackett, Paul Kehler, R.N. Curran, G.A. Forster and C.L. Livengood, "Applications of the Pulsed Neutron Activation Technique for Flow Measurement at EBR-II", ANL-CT-77-52, (July 1977).
17. C.C. Price, Paul Kehler, J.I. Sackett, "Fluid Flow Measurements at EBR-II Using Pulsed Neutron Activation", ANS Transactions **23**, 117 (1976).
18. G.A. Forster and Paul Kehler, "Sodium Flow Calibration Using a Pulsed Neutron Activation Technique on a 400 mm (16 inch) Pipe at LMEC", ANL-CT-78-9, (November 1977).
19. Paul Kehler, "Measurement of the Emergency Core Coolant Bypass Flow On the LOFT Reactor", NUREG/CR-0208, ANL-CT-78-37 (1978).
20. Seminar Proceedings: I. Pulsed Neutron Uranium Borehole Logging with Prompt Fission Neutrons (PFN), II. Neutron Tube Technology for PFN Logging Equipment, SANDIA Laboratories, Albuquerque, N.M., SAND77-0300 (February 1977).
21. F.M. Bacon and J.B. O'Hagan, "Ion Source Development for Uranium-Logging Neutron Tube", SAND76-0731 (March 1977).
22. K.W. Ehlers et.al., "Development of an Occluded Gas Ion Source", Rev. Sci. Instrum., **29**, 614 (1958).