Multiphase Flow Measurement by Dual Gamma Ray Tomography

Wu Yingxiang, Cui Bin*, Li Donghui, H. Inaki Schlaberg**, Zheng Zhichu, Zhong Xingfu

Institute of Mechanics, Chinese Academy of Sciences, Beijing 100080, China
**Liaohe Oilfield, Panjing 124010, China*
***Institute of Particle Science and Engineering, University of Leeds*

Abstract This paper describes some of our research in three phase flow-rate measurement of oil/gas/water by processing tomography of dual gamma ray, including the instrumental designs on the technique of photons pulse counter, signals of sensor, preamplifier, filter and shaping amplifier, DC base shift correcting circuit, narrow windows of energy spectroscopy, programmable pulse count acquisition system; the FPGA (Field programmable gate array) based data acquisition and processing system for gamma ray tomography; and the oil-water-gas three phase volumetric fraction distributions from experiments on a test flow loop.

Key words: Multiphase flow, flow-rate measurement, gamma ray, process tomography

INTRODUCTION

Multiphase flow measurement, especially oil/gas/water flow-rate measurement is a significant issue in oil industry. Operators in oil companies and designers of oilfield facilities are keen to seek for the multiphase metering technology to simplify the design and improve the control of production facilities. They considered that, unless multiphase metering techniques were mature, it would be virtually impossible to know what was happening in sub-sea production systems or on the unmanned satellite oil production platforms.

Multiphase metering systems used in harsh environments of offshore environment must possess ability to measure accurately flow-rates of each phase in all flow regimes and it should not be affected by changes in fluid properties like density, viscosity, surface tension, and dielectric properties. In addition, they should also be required with non-intrusive property and robust design for convenience in operation and on-line maintenance. In spite of the large number of solutions that have been proposed in recent years, no commercially available three-phase flowmeter yet meets all these requirements.

The multiphase meters can be based on different principles. To some extent a specific principle is used to measure only in a limited range of phase fractions. Some of the available products require a preconditioning of the flow, which is a severe limitation for most applications. Out of the possible measurement principles electromagnetic interaction is promising for cases where the fluid components have distinct dielectric properties. Depending on the application and materials properties one can distinguish resistive, capacitive, radio frequency (RF), microwave, infra-red, optical, ultra-violet, x-ray and gamma-ray sensors[1-4].

Process tomography is another discipline which has seen a significant growth over the last ten years, with laboratory imaging systems having been developed for a number of multiphase applications. It is not yet clear whether such techniques can be used to measure component flowrate any more accurately than existing solutions. However, these techniques may have the potential to enhance the performance of existing commercial flowmeters[5~9].

Gamma ray tomography is a potential method that may be applied to measure the distribution of phases respectively the hold-up of liquid or gas in multiphase transportation pipelines. It is a measurement technique to provide the detailed information on phase distributions of the cross-section of pipeline.

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In this paper, we give some research results in three phase flow-rate measurement of oil/gas/water by processing tomography of dual gamma ray, including the electronics design for a dual energy gamma ray, instrumental designs on the technique of photons pulse counter, signals of sensor, preamplifier, filter and shaping amplifier, DC base shift correcting circuit, narrow windows of energy spectroscopy, programmable pulse count acquisition system; the FPGA (Field programmable gate array) based data acquisition and processing system for gamma ray tomography; and the oil-water-gas three phase volumetric fraction distributions from experiments on a test flow loop.

ELECTRONICS DESIGN FOR DUAL ENERGY GAMMA-RAY

In the instrumental design of dual energy gamma ray system, the important parameters to be considered are:

- selection of detector;
- design of preamplifier;
- design of filter and shaping amplifier;
- design of DC base shift correcting circuit;
- design of dual channels analyzer;
- design of programmable pulse counter data acquisition system.

1. Detector

A dual energy γ ray is used as the detecting source of the PT measurement system. It is comprised of two radioactive isotopes of ^{241}Am and ^{137}Cs which have emission energies at 59.5keV and 662keV. NaI (Tl) crystal is selected as the scintillator for its highest detection efficiency and short decay constant to get high count rate and avoid pulse pile up or saturation when the system is operated in count mode. A photomultiplier tube is used for multiplication of the light emitted by scintillator and NaI (Tl), one kind of inorganic scintillators with high density and high atomic number, is adopted to detect gamma rays.

The photo multiplier tube (PMT) consisting of an evacuated glass tube with photocathode at its center and several dynodes in the interior is an integral part of a scintillation counter which amplifies an incident pulse of visible light by a factor of 1000,000 or more in times of 1 ns.

The photons produced in the scintillator enter the PMT and hit the photo cathode. The electron emitted by the photocathode is guided by an electric field towards the successive dynodes. The voltage difference between the two successive dynodes is of the order of 80–120V. Typical commercial photo tubes may have up to 15 dynodes.

2. Amplifier

As the signals from the detector are very weak, usually in mV range, an amplifier is required to increase the amplitude of pulse from detectors by a factor of thousand or more to a few volts to meet the needs of the analyzer that follows the amplifier with the provision for a gain selection and pulse shaping time constant.

The pulse signal from amplifier is a series of negative pulses with a significant positive DC base shift, the amplitude of pulses corresponds to the entrance photon energy.

3. DC base shift correcting circuit

In dual energy gamma ray system, because of the high accuracy requirement of spectrum resolution, the DC base shift is thereby very harmful for pulse altitude measurement, thence a DC base restore circuit is needed to be used to isolate the DC base shift.

In general, a RC differential circuits can be used as DC isolation. If the RC circuit time constant is much shorter than the signal pulse interval, the voltage of capacitance drops to the input signal base rapidly, then the DC base can be restored. As the time constant RC is much shorter than the pulse assert time, the output pulse of RC circuit becomes narrow and sharp. There should be troubles for the behind spectrum analyzer. A improved CD circuit was presented in this study which applied a nonlinear component of diode to replace the resistance in RC circuit. The positive resistance of diode is large when it is not leaded, which will produce a large shift rate than RC circuit.

4. Filter and shaping amplifier

To improve the signal to noise ratio and to shape the pulse into a Gauss-like curve, a filter and a shaping amplifier is engaged in frequency analysis to eliminate some frequencies from the signal. A pole-zero cancellation technique is adopted here.

The output pulses from the shaping amplifier are inverted to positive pulses and are amplified the amplitudes to 0~8V. The pulses are shaped to a Gauss-like curve and are adjusted to only 1~2us wide to avoid pulse pile up for the case of high count.

5. Dual channel analyzer

Dual channel analyzer is an important unit in the gamma ray spectrometer to select the amplitude (and hence the energy) for output pulses from the amplifier. We set two narrow windows for the analyzer to get lower discriminator and upper discriminator level selections. When pulses appear on or out of the shaping amplifier, the lower and upper level discriminators operate, only the photons with energy above the lower threshold energy and below the upper threshold can be counted using the window operation thereby rejecting the unwanted low/high energy pulses.

As the dose of ^{241}Am and ^{137}Cs are 100 mCi and 20 mCi, the peak of ^{241}Am is higher than ^{137}Cs's, and the ^{241}Am uses narrower voltage window than ^{137}Cs, which means that the sensor of scintillator has higher energy resolution and more efficient for ^{241}Am than for ^{137}Cs.

Only the pulse of the amplitude within the low threshold and up threshold can be recorded, lower or upper pulses will be rejected by the discriminator. The discriminator circuit comprised of two high speed voltage comparators and associated logic circuits, two adjustable reference window voltages are provided.

DATA ACQUISITION SYSTEM

The data acquisition system includes two parts, one deals with the detection signals as a programmable pulse counter system, the other communicates with a host computer which sends parameters, such as the acquisition time frame, and sends commands, such as the start signal of an acquisition cycle and collects the acquired results.

1 Programmable pulse counter system

An Intel Pentium industrial control computer is used with eight boards of 32 channel 16 bit pulse counter in its ISA bus as signal acquisition system. The counter's latch time and counter bit length are programmable, the integral time for every channel is programmable as well. The programmable counter board is based on the chip of 8253 which have three channels of programmable interval timer/counter. In order to avoid the pulse deforming (only 100~200ns), digital logic isolation is necessary for the transmission from shaping amplifier to the counting board. An ultra high speed (10MBd) photo coupler 6N137 is employed in the board therefore noise and disturb are eliminated.

Another important constituent in the data acquisition system is the software that enables users to select above control parameters, acquire the data and does further arithmetic.

This is a conventional way of data acquisition based on the technique of photons pulse counter, corresponding to the multi-CPU data acquisition system. It has a simple structure and a low data flow rate from the unclear instruments to computer.

One processor board of the acquisition system is dedicated to perform the communication with the host and interfaces with the rest of the channels of the system. This controller board distributes the commands for the host to each of the channels via a backplane that connects all the boards of the system.

2 FPGA (Field programmable gate array) based data acquisition and processing system

The data acquisition system communicates with a host computer which sends parameters and commands. One processor board of the acquisition system is dedicated to perform the communication with the host and interfaces with the rest of the channels of the system. This controller board distributes the commands for the host to each of the channels via a backplane that connects all the boards of the system.

Each channel of the tomography system can operate independently and report the results to a controlling processor which will communicate with a host computer.

After simple signal conditioning to bring the voltages within the range of the A/D converter specification a dual channel converter chip takes the data of two detectors to the FPGA chip. The FPGA is connected to a DSP which can operate on the sample data or instruct the FPGA to perform operation. A backplane connector provides the bus for communication between the channels and the main controlling board. Although the connector is physically attached to the FPGA, it is the DSP which controls the communication. The A/D converter chip selected operates at 20MSPS with 12 bits resolution. It is pin compatible with 14 bit devices and devices that can sample at rates up to 65MSPS.

The task of the acquisition channel is to count the number of pulses at each energy level and transmit these two values to the host. Combined with the results from other channels these will be used in an image reconstruction algorithm. The procedure for obtaining the information is to first detect the peaks from the data stream of the A/D converter and record its maximum amplitude.

As the data stream enters the FPGA at 20MSPS, the DSP which operates at 200MIPS only has 10 clock cycles to implement the peak detection algorithm between incoming samples. This may prove challenging and also limits the functionality of the algorithm. A further demand on the resources is the fact that each A/D converter has dual inputs and delivers data to the FPGA (and the DSP) from two separate detectors.

The dual data stream may however be compensated by the fact that the DSP has a dual core and can simultaneously operate on two separate data operands albeit with the same instruction. In other words the DSP uses a SIMD (Single instruction, multiple data) architecture that could be exploited by the dual data stream of the A/D converter.

An alternative method to implement the peak detection algorithm makes use of the FPGA. In this way the resources of the device can be employed to operate on the data in parallel rather than the sequential nature of the DSP program. The number of clock cycles can be reduced by employing a pipelined design. However this is at the expense of increased use of internal resources and a longer latency depending on the number of stages in the pipeline. For example, if the design has a five stage pipeline, it would take five cycles for the first data item to emerge. However, a delay of a few clock cycles is not significant in the whole acquisition cycle.

DYNAMIC MEASUREMENT OF VOLUMETRIC FRACTIONS OF OIL/GAS/WATER MIXTURES

1 Dual energy theories

The measurement of component ratios in multiphase flow using γ-ray attenuation was first suggested by Abouelwafa and Kendall (1980), and the technique is used in many current multiphase metering systems. Attenuation of a beam of γ-rays by a material of thickness t is given by:

$$I(E) = I_0(E)B\exp(-\mu(E)t))$$

where I(E) is the transmitted intensity, I0(E) is the incident beam intensity, μ(E) is the linear attenuation coefficient of the attenuating material at energy E and B is the buildup factor, which takes account of radiation scattered into the detector. For oil/water/gas three-phase flow, the attenuation coefficient of the mixture μ(E) is represented by

$$\mu(E) = \alpha\mu(E)_o + \beta\mu(E)_w + \chi\mu(E)_g$$

where μ(E)o, μ(E)w and μ(E)g are the linear attenuation coefficients of the oil, water and gas, and α, β, χ are the respective volume fractions. The transmitted intensity I through a thickness t of a oil/water/gas mixture is therefore

$$I = I_0\exp[-(\alpha\mu(E)_o + \beta\mu(E)_w + \chi\mu(E)_g)t]$$

if the build-up factor is eliminated through good collimation at the source and detector. After the transmitted flux I1 and I2 at two energies E1 and E2 is measured, the volume fractions can be calculated if the linear attenuation coefficients of the flow components at E1 and E2 are known since

$$\ln(I/I_0)_1 = -\lfloor\alpha\mu(E_1)_o + \beta\mu(E_1)_w + \chi\mu(E_1)_g\rfloor t$$

$$\ln(I/I_0)_2 = -\lfloor\alpha\mu(E_2)_o + \beta\mu(E_2)_w + \chi\mu(E_2)_g\rfloor t \quad \text{and} \quad \alpha + \beta + \chi = 1$$

There are three equations with three unknown's volumetric fractions α, β and χ.

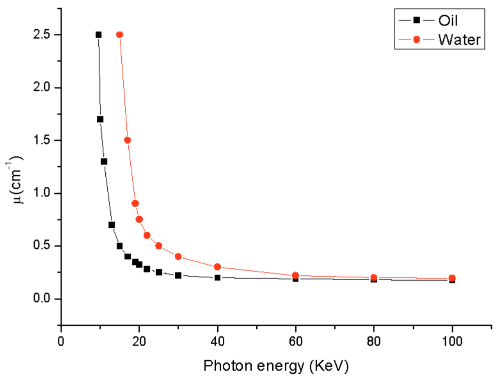

Fig.1 Water and oil attenuation coefficients

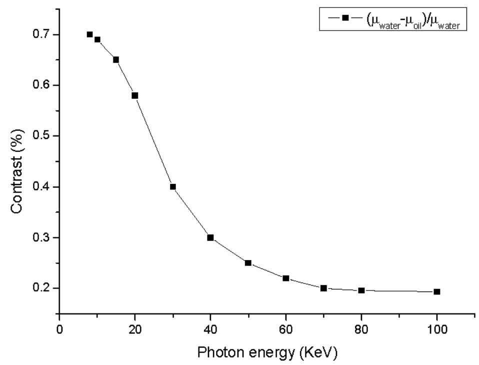

Fig.2 Radiographic contrast between oil and water

The linear attenuation coefficients of water and mineral oil (kerosene) over the same energy range reveals the differences in the photon absorption can be used to distinguish them. Fig.1 shows the photon attenuation of water and oil. Since the photoelectric interaction is a stronger function of photon energy and atomic number than the

Compton interaction, there is greater contrast in the linear attenuation coefficients of oil and water in the region where the photoelectric effect dominates the interaction cross-section of both materials[10].

2 Experimental arrangement

The oil-water-gas three phase flows are very complex and it is impossible to test all the flow rate combinations for each phase media. In order to study the three phase materials attenuation character, an experimental arrangement was designed as shown in Table 1, including total 6 groups of measurements in the experiment. All the flow rate data are superficial flow rate obtained from flow meter of each phase.

Table 1 (Gas1=20SL/min, Gas2=100SL/min)

Oil	Water							
0.75m³/h	2.5m³/h	3.75m³/h	5m³/h	6.25m³/h	7.5m³/h	8.75m³/h	10m³/h	12.5m³/h
1.5m³/h	2.5m³/h	3.75m³/h	5m³/h	6.25m³/h	7.5m³/h	8.75m³/h	10m³/h	12.5m³/h
3.6m³/h	2.5m³/h	3.75m³/h	5m³/h	6.25m³/h	7.5m³/h	8.75m³/h	10m³/h	12.5m³/h

3 Results on three phase flows

Six groups of oil-water-gas three phase flow were surveyed by dual energy γ ray system. The results of three phase volumetric fraction of oil-water-gas multiphase flow are shown in Fig.3.

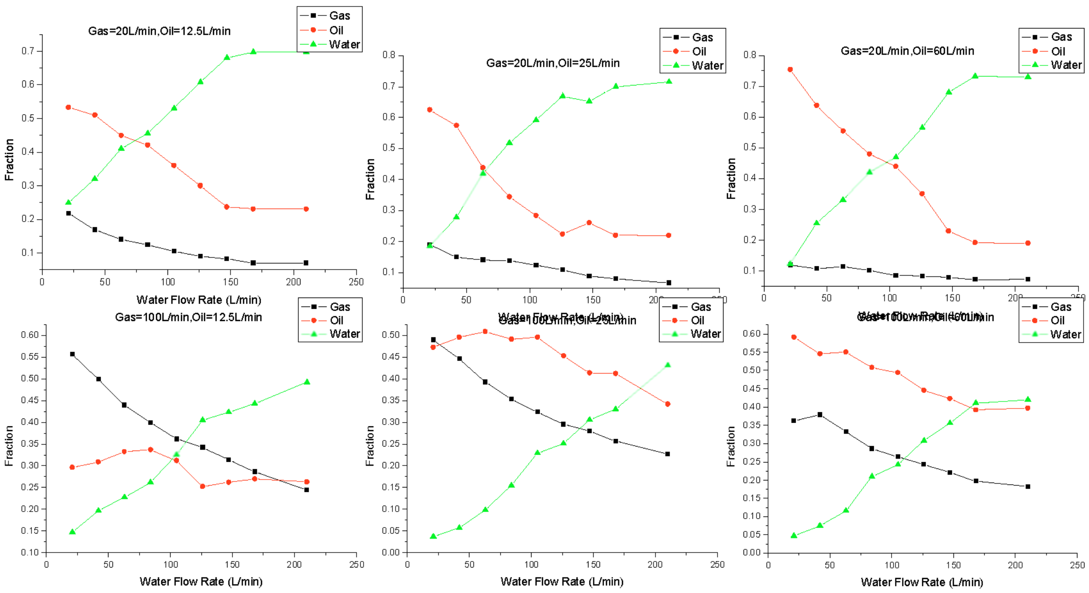

Fig.3 Volumetric fractions of oil-water-gas multiphase flow

In the top row of curves in Fig.3, the gas flow rate is fixed in 20L/min; in bottom row, the gas flow rate is increased to 100L/min. The oil flow rate is changed from 12.5L/min, 25L/min to 60L/min respectively in the diagrams of both rows from left to right in Fig.8. The water flow rate is increased from 21L/min to 210L/min in 9steps as shown on the X axis in each diagram. The sum of gas, oil and water volumetric fraction is equal to 1, and the measurement integral time is 200s in this experiment.

It is easy to find that with the increasing of the oil flow rate as shown in Fig.8 from left to right curves in both rows; the total liquid flow rate increased, and then the gas volumetric fraction decreased. This is because gas is a compressible fluid, when the total liquid fraction increased; the pressure inside the pipe goes up, thus the volume fraction of gas decreased.

The oil volumetric fraction also increased as expected as shown in Fig.8 from left to right curves in both rows. The oil flow rate is changed from 12.5L/min, 25L/min to 60L/min, and the dual energy γ ray system gives out a correct response to the fraction changes. This shows a reasonable measurement accuracy. But there are also some significant error points on these curves; some curves do not look smoothly as they should be.

CONCLUSIONS

A study on oil-water-gas three phase flow measurement system by a dual energy γ ray tomography is presented in this paper. From the study, some conclusions can be drawn that:

(1) There are several key points in the nuclear instrumental designs, including DC base shifting and pulse shaping. An appropriate treatment of above questions will increase the accuracy of the dual energy gamma system.

(2) The system uses dual channel A/D converter chips that operate at 20MSPS and 12 bit resolution, but can be upgraded to 65MSPS and 14bits without hardware modifications other than replacing the pin compatible converter chip. The components used are widely available and result in a low cost per channel. The channel hardware has been successfully tested with a standard signal generator. The data processing for the peak counting has been implemented on the FPGA resulting in a fast and flexible processing of the sensor information.

(3) The algorithm has been simulated on the FPGA platform with data obtained during previous tests on a flow loop and the results show the peaks of energy levels that were expected. Further work on this systems needs to be performed by integrating the data of multiple channels and performing experimental evaluation with the gamma ray sources on the flow loop.

(4) It is clear that the oil-water-gas three phase flows are very complex. Not only there are speed shifts and velocity differences between every phase media but also there are phase volumetric fraction changes in the cross section of the pipe. Until now there are no other more efficient and convenient way that can be used to measure the oil-water-gas multiphase flow. The dual energy γ ray is a promising technique for the purpose of simple and fast estimating the phase fractions of the oil-water-gas multiphase flow.

(5) There is statistical fluctuation in γ ray source emission intensity. This requires a long integral time in measurement to reduce the error, and it is difficult to get short time measurement information, only the long time average results are reliable unless uses large activity γ ray source, but this will bring the new problems related to system cost and radioactive safety protections.

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