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Terahertz PT technology for measurement of multiphase flow and its infrared simulation*

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Abstract: Terahertz process tomography (PT) is a new technology for multiphase flow measurement. T-ray PT prototype based on analysis of the T-ray's merits was proposed and an NIR PT simulation system was developed in this paper. The architecture, algorithm and characteristics of the simulation system were studied through experimental test. Evaluations of the simulation system performance and corresponding promotional approach were made. It was shown that the solution of simulation system could be adapted for THz PT technology, and that the experimental results proved that the simulation system itself is suitable for parameter measurement of two-phase flow.

Key words: T-ray, Near infrared, Process tomography (PT), Multiphase flow
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INTRODUCTION

Multiphase flow is normal phenomena in industry. In past decades, investigations on multiphase flow measurement were mostly focused on the process tomography (PT) technology (Li, 2000), including electrical capacitance PT, electrical resistance PT, electromagnetism PT, X-ray PT, Ultrasonic PT and so on. Unfortunately, these PT technologies are not good enough to meet industrial requirements because of the image reconstruction quality, cost or safety.

In recent years, optical computed tomography (CT) technology with features of high quality and non-destructiveness is widely studied in many fields. It is usually based on the following optical propagation effects within the object materials, e.g. reflection, refraction, diffusion, absorption, diffraction, etc. The image of the object structure can be reconstructed on the basis of the obtained information on these effects (Hebden *et al*., 1997; Arridge and Hebden, 1997). There are various imaging methods, such as diffusion optical tomography (Schweiger *et al*., 2003), optical coherent tomography (Schmitt, 1999), optical Doppler tomography (Chen *et al*., 1999), and so on. Although optical CT technology was developed for biomedical applications originally, it can also be used in multiphase flow parameter measurement. Terahertz PT technology may be a solution according to Terahertz waves' special physical characteristics (Chen and Zhou, 2004).

Terahertz waves are electromagnetic waves at frequencies ranging from 300 GHz to 10 THz, which lie between the infrared and microwave (Jia *et al*., 2002). It can also be called T-ray or THz for short. Terahertz waves have some fantastic physical characteristics. It has features of optics and microelectronics. For example, T-ray has penetration ability just like X-ray, which means T-ray can pass through material that is opaque to visible light like fabrics, plastic, wood, ceramics, etc. So that it can be used in tomography technology. T-ray will be safer than X-ray during applications because the average energy

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of its phonon is much lower than X-ray. Furthermore, T-ray has quasi-optic features like visible light and infrared too. It can be focused, collimated and reflected by special instrument. So T-ray may be an ideal medium for non-destructive detection. Nowadays, possible applications of T-ray are being widely studied.

T-RAY PROCESS TOMOGRAPHY SYSTEM

T-ray PT is similar to X-ray PT as they both can be used to reconstruct object section image with the same high image quality. Both of them need some kind of scan system to get enough projection data for image reconstruction. But except for high image reconstruction quality, traditional X-ray PT system has several shortcomings during its industrial applications, e.g. complicated scan model mechanism, slow imaging speed and its high cost. In actual industrial applications such as parameter measurement of multiphase flow, system cost and response speed are also as important as image quality.

Due to the quasi-optic feature of Terahertz waves, quasi-optic scan model can be used in the T-ray PT system. That is one of the most important features for T-ray PT to be applied in industrial fields. With the quasi-optic scan model, the structure of T-ray PT system can be simpler and more flexible than that of X-ray PT system. Then, system stability and image reconstruction speed can be guaranteed at the same time.

A scan mode of T-ray PT system focused on a particular application of multiphase flow measurement is described in Fig.1. In this prototype system, several T-ray sources and a set of T-ray receivers are distributed uniformly around the pipe. Every T-ray source has a quasi-optic deflection system to do fan shape sector-scan, scan ranges of these sources will be crossed and overlapped. The numbers of T-ray sources and receivers depend on the pipe's diameter and system's expected image quality. Differing from Fig.1b, Fig.1a has a large scanning angle and requires fewer T-ray sources. The scan distribution of large angle scan mode within projection field is much more uniform than that of small angle scan mode. But it is difficult to achieve the uniformity of source distribution.

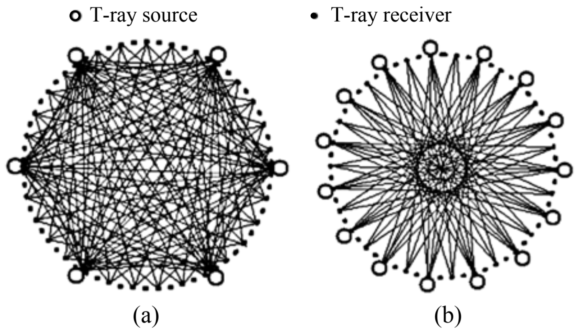

Fig.1 Supposed scan mode of T-ray PT. (a) Large angle scan mode; (b) Small angle scan mode

In contrast with the synchronization rotation scan mode of traditional X-ray PT, quasi-optic scan mode of T-ray PT system is steadier and simpler. Higher stability and response speed along with higher imaging quality are its valuable virtues for T-ray PT to be applied in industrial fields.

SYSTEM FEASIBILITY ANALYSE

Performance of Ray PT system mostly depends on two factors, one is quality and quantity of scan data, and the other is the image reconstruction algorithm. Differing from the traditional X-ray PT system, the T-ray PT system is a kind of static scan mode, using limited numbers of sources and receivers. The scan uniformity mostly depends on the number of sources, and the scan density mainly depends on the number of receivers. Thus, the balance between expected performance and system cost should be considered. With the high scan speed provided by quasi-optic scan mode, the T-ray PT system can use more exact image reconstruction arithmetic to obtain the appropriate response speed at the same time.

The feasibility of this system is not a problem. But the present generation of T-ray mostly depends on complicated and expensive ultra fast laser system. The considerable cost of T-ray equipments prevents it to be actually used in industrial applications. Fortunately, Terahertz technologies, such as quantum-cascade laser technology, solid-state Terahertz sources, micro-machined Terahertz antenna (Muller and Lau, 1998), are being promoted very rapidly today. The stacking technique of combining a micromachined Terahertz antenna with a silicon photonic band gap backing plane, provides the possibility of laying out an array of Terahertz detectors into a CCD mode. This approach would result in a cheap, compact configuration of Terahertz detector chip that could be as small as 20 mm square for a 100-element array. So this T-ray PT system is feasible but will take time to lower its cost to make compact its configuration to an acceptable level.

NEAR INFRARED SIMULATION SYSTEM

In this paper, a near infrared (NIR) PT prototype system as a simulator of T-ray PT is proposed. NIR laser source and sensor have the advantages of low cost, compact structure and very high working frequency. The wavelength of NIR is very close to that of T-ray's. So NIR laser is suitable medium to be adopted in this simulation system.

Scan mode and its structure of NIR PT

For the NIR laser PT simulation system, there are two approaches to realize sector-scan, as shown in Fig.2. Using fan-beam NIR diode laser in point-to-line mode, or using line-beam NIR diode laser with optical scan system (for example, rotary reflection mirror) in point-to-point mode. The first approach is serial scanning and parallel receiving. It is simple but difficult for optical reflection and refraction effects. These effects will disturb the sensors from receiving genuine projection signals. With the feature of parallel scanning and serial receiving, the second approach is more complicated than the former one, but can avoid the disturbance of optical reflection and refraction effects during data collection. So the latter approach is used in our test system.

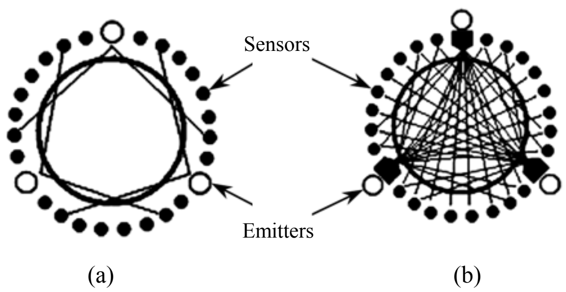

Fig.2 The scan modes of NIR PT. (a) Fan-beam; (b) Line-beam

As shown in Fig.3, the supposed test area is a circle with diameter of 50 mm. There are 6 NIR diode lasers and 48 NIR diode sensors located uniformly around the pipe. The wavelength of NIR laser is 780 nm with beam diameter of 1 mm, and its power output is 10 mW. Every emitter is equipped with a corresponding optical scan system. The optical scan system uses normal rotary six-sided prisms. The scan sector of every emitter overlays 24 sensors with scan angle of 90°.

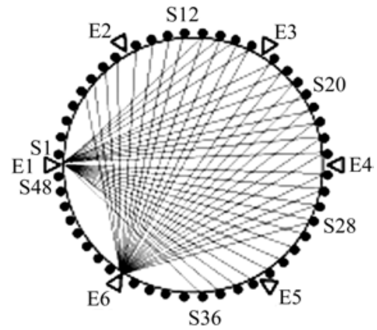

Fig.3 Emitters and sensors array of simulation system

The hardware structure of NIR PT simulation system is shown in Fig.4. There are three subsystems that can be defined: The control and interface subsystem (CIS), the signal collection logic control subsystem (SCS), and the image reconstruction subsystem (IRS). Signal collection process should be logically matched, and is controlled by SCS accurately. Every emitter has a corresponding SCS. They have the same structure but work independently. IRS reconstructs images based on projection data collected by SCS. CIS harmonizes operations of SCS and IRS, and provides interface services such as system initialization, configuration and communication.

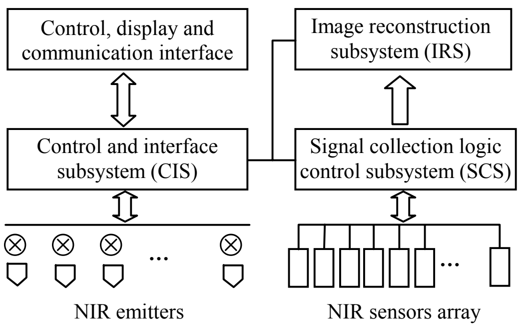

Fig.4 Hardware structure of NIR PT

Imaging algorithm of NIR PT

Simplicity of imaging algorithm is very important to image reconstruction speed, especially with a large amount of projection data. Thus, two-value filtered back projection image reconstruction algorithm is applied in this test system. It is a kind of simplified back projection algorithm with features of simplicity and speediness.

Two-value filtered back projection algorithm is based on the two-value character of the object image and projection data. Our test object is a two-phase flow, and two values, 0 and 1 can be used to express test object image and projection data. The image reconstruction algorithm is illustrated in Fig.5.

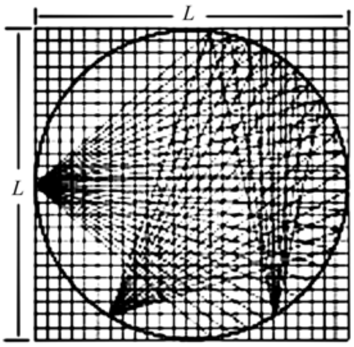

Fig.5 Image reconstruction algorithm illustrations

Suppose $\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{C}$ are $L\times L$ square matrixes, operator $\odot$ represents an operation as follows:

$$\boldsymbol{C}=\boldsymbol{A}\odot\boldsymbol{B}$$

then

$$c_{ij}=\begin{cases}1 & a_{ij}=1 \text{ or } b_{ij}=1\\ 0 & a_{ij}=b_{ij}=0\end{cases} \tag{1}$$

where a_{ij}, b_{ij} and c_{ij} are elements at row i and column j of matrix $\boldsymbol{A}$, $\boldsymbol{B}$ and $\boldsymbol{C}$ respectively.

The external square of the test pipe is divided into $L\times L$ pixels. $\boldsymbol{P}_k$ (k=1, 2, …, N) is defined as the projection matrix of projection direction k (different emitter has different projection direction). So $\boldsymbol{P}_k$ is an $L\times L$ square matrix, whose element values are 0 or 1, depending on back projection values with projection direction k. N is the number of projection directions, which is equal to the number of NIR emitters in our test system. If the $L\times L$ square matrix $\boldsymbol{H}$ represents the test object image, the result is as follows:

$$\boldsymbol{H}=\boldsymbol{P}_1\odot\boldsymbol{P}_2\odot\cdots\odot\boldsymbol{P}_N \tag{2}$$

Variable L represents the dimensions of reconstruction image matrix. Its value is determined by system image reconstruction resolution. The resolution of sector-scan is an average. Assume test object diameter is D (mm), laser beam diameter is B (mm), sensor number is S, image reconstruction resolution is I (mm). The formula correlating those parameters can be expressed as follows:

$$I=\begin{cases}B+\dfrac{\pi D-SB}{2S} & B<\dfrac{\pi D}{S}\\ B & B\geq\dfrac{\pi D}{S}\end{cases} \tag{3}$$

The two-value filtered back projection algorithm can be used in many types of two-phase flow measurement for our simulation system. The optical effects of refraction, reflection and absorption have almost the same result in the point-to-point scan mode, as shown in Fig.6. The condition is that the flow of high bulk concentration phase must be transparent (or sub-transparent) to NIR.

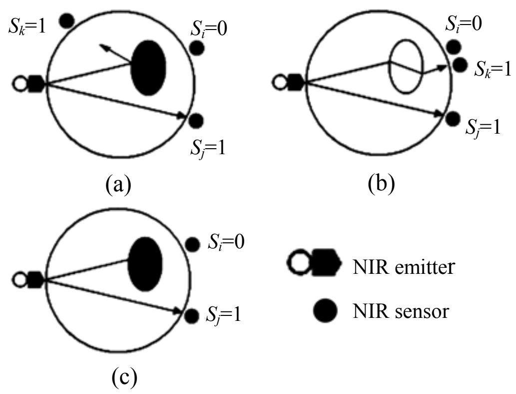

Fig.6 Different propagation effects of NIR laser. (a) Reflection effect; (b) Refraction effect; (c) Absorption effect

The two-value filtered back projection algorithm is also suitable for the imaging of gas-solid flow. The condition of this application is that the diameter of solid particles should be larger than a certain size. If their sizes are much smaller than NIR laser beam diameter as shown in Fig.7, the particles cannot change the propagation direction of the NIR laser beam, and the particles concentration of the projection route has approximate linear relation with the intensity of the projection signal. Normalizing projection data into a two-value form will lose the information on solid concentration.

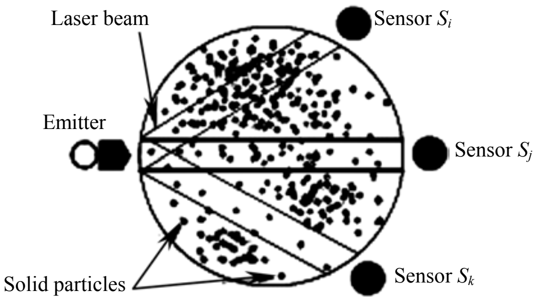

Fig.7 Projection illustration within gas-solid flow

EXPERIMENT RESULTS AND THEIR ANALYSIS

The tests on the absorption effect were carried out in our simulation system. The test area was a circle with diameter of 50 mm. Three opaque cylinders were placed in the test area in order to simulate two-phase flow. The diameters of the 3 cylinders were 3 mm, 5 mm and 7 mm respectively. In our test system, S=48, B=1 mm, and D=50 mm. The reconstruction speed of this test system was about 100 images per second and its identification power was just 2 mm. The test results and their original images are illustrated in Fig.8.

As shown in Fig.8a, the imaging accuracy of two-value filtered back projection algorithm is satisfactory for thin two-phase flow, but Fig.8b illustrates that this algorithm is not excellent for complex distribution or complex shape of two-phase flow. If the observed objects are adhered to each other, it is difficult to separate them because two-value projection data only contains the part of medium distribution information along the projection route. It is necessary to develop a more effective algorithm to de-couple object conglutination.

Certainly, projection data quantity and quality still depends on emitter number. So increasing the emitter number can improve the system's quality. Otherwise, modern infrared laser equipments such as CCD line sensor, which can be focused to the μm level, can be applied to increase the quantity of projection data and improve its solution accuracy effectively.

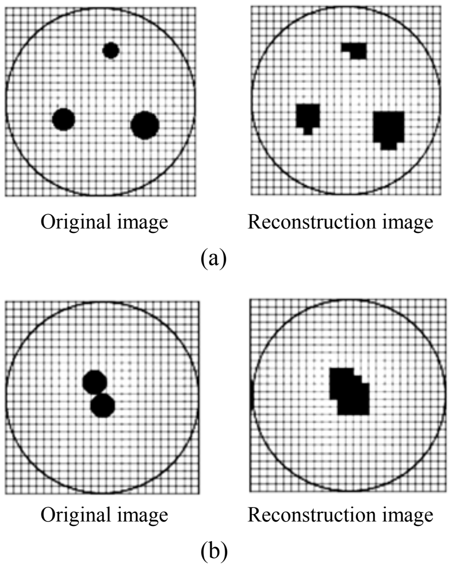

Fig.8 Test results and their original images for (a) thin two-phase flow; (b) complex distribution or complex shape of two-phase flow

System response speed is another important factor during its industrial applications. It mainly depends on the speed of scan system, the response speed of sensor and the operation speed of image reconstruction algorithm. The working frequency of optical sensor can be MHz or even GHz. So the most important factor of our test system is the scan speed, which depends on motor rotation speed and the number of sides on the prism. The scan frequency was 300 Hz in our test system. It can satisfy the requirements of most two-phase flow measurement applications. If not, the micro-machined mirror optical scan system can be applied to improve the scan speed (Su *et al.*, 1999). Its working frequency can be kHz.

CONCLUSION AND PROSPECTS

An NIR PT system as a simulator of T-ray PT was developed. Several valuable merits of T-ray and its industrial applications were demonstrated by both theoretical analysis and simulation test.

Optic scan model can largely improve the simplicity and flexibility of optical PT system, and point-to-point scan mode can reduce the influence of optical refraction and reflection effects. Two-value filtered back projection algorithm is very simple and fast, and can guarantee the image reconstruction speed especially for large amount of projection data. It will be useful for two-phase flow measurement. But its image reconstruction accuracy should be enhanced.

THz and NIR are both electromagnetic waves with frequencies almost adjoining the electromagnetic spectrum. Their transmitting characteristics can be analyzed by the principles of Maxwell electromagnetic theory and wave optics theory (Wang *et al*., 2003). The solution of the NIR PT simulator will be applicable to THz PT if there are suitable THz laser sources and THz sensors, and then the architecture of our NIR PT system could be adapted for THz PT also.

THz PT and NIR PT technology are new approaches for the parameter measurement of multiphase flow. Research works proved that the proposed PT system is suitable for two-phase flow measurement. Compared with the existing PT technology, this prototype system can get very high imaging speed and resolution with acceptable cost. But how to enhance its image reconstruction accuracy, how to improve the response speed, and how to actually combine with T-ray are main subjects that should be studied in future investigations.

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