Development of discrete-beam gamma ray method to measure void fraction of two-phase flow

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Abstract

This paper explains a method to measure void fraction of two-phase flow using multi-beam gamma ray densitometer. It is required for evaluation of the mass flow rate of two phase flow to measure its density by using signals from several sensors such as the venturi and turbine meter. Conventionally, the densitometer with single beam or multi beams less than three has been used, but we wish to confirm possibility to get the tomography information by increasing the number of beams. Main research contents are development of the image reconstruction method for the radiation, optimization of the number of beams, characteristics of responsiveness about flow patterns of two phase flow, and effect of filter.

A computer code for this purpose is developed and evaluated with various flow patterns including bubbly flow, slug and annular flow, and stratified flow. It was found that the minimum number of beams are 30 and it could be reduced by developing a proper filter and advanced image processing technique.

1. Introduction

It has been informed that is very difficult that measure the mass flow rate of two phase flow using single sensor because there are three variables to be measured: void fraction, the velocities of each phase. As listed in Table 1, there are many methods for the mass flow rate measurement. Except the comprehensive method, the measurement of void fraction is very important to the restricted methods. They use the information of the momentum flux from the drag disk, venturi, or orifice, the two-phase velocity from turbine meter, and the void fraction from the gamma densitometer. The uncertainties in the model for evaluation and the distortion in flow by the sensors could produce a large error in measurement.

As listed in Table 1, though there are many devices for the flow rate measurement, the source of uncertainties could not be removed in the systematic way. In cas of TMFM which measures it directly, but it distorts flow field severely. Only the gamma densitometer is reliable one interms of the flow filed preservation. However, its output quality depends on the flow regime, recentely, the number of beams are increasing. The devices produces pressure drop such as venturies, orifices, drag disks also, possess large uncertainties in understanding two phasef low effect. Few papers are founding for the bubble deformation and migration in the venturi flow channel. Alos, the transienet effect of turbine meter is modelled and anlayzed by Lahey et al [ ] in the form of too comple to be used for the data acquisition. Therefore, Rohani correlation is widely accepted because of its simplicity.

	Comprehenbsive method		Restricted Method	
Examples	TMFM	Radionuclide technique	Drag Disk + Turbine Meter + Gamma densitometer	Drag Disk +Gamma Densitometer
Measured Variables	M	$\alpha,\ v_G,\ v_L$	$(\rho v^2)_{DD},\ v_{T,}\alpha$	$(\rho v^2)_{DD}, \alpha$
Evaluation Equations	$G_{TMFM} = \frac{M}{A\omega r^2}$	$G = \alpha_\gamma \rho_G v_{RG} + (1-\alpha_\gamma)\rho_L v_{RL}$		$G = \sqrt{\rho_\gamma (\rho v^2)_{DL}}$
Region of Validity	All Flow regime			Homogeneous flow
Evaluation Procedure	Direct, without modelling		Indirect, with modelling $v_T = \alpha v_G + \alpha_L v_I$	Direct, Model in Evaluation Equation
Requirement for two-phase Flow calibration	Two-phase flow calibration set Absolutely necessary		Two-phase flow calibration Required for Every Geometery	

The present study is a part of activity in the research of the optimum sensor combination for measuring the mass flow rate in the two-phase flow. Also, the present work could be applicable to develop the density-meter using soft radiation.

The main question to be resolved in this study is that, how many beams are required to measure the reliable two-phase density without flow regime dependency. The mechanical driving radiation tomography for the medical purpose is not useful for the two-phase flow because the density in the two-phase flow varies according to the bubble motion. In terms of density, there is no steady state because the bubble is discontinuous object. If we could use small numbers of beam, the system does not need any mechanical moving parts. By increasing detectors, the simultaneous data gethering could provide real time capability. So the image reconstruction with the discrete signals should be developed to know its applicability to the two-phase flow analysis and to develop methods to enhance its predictability.

2. The multi-beam Gamma Density-meter for CT

2.1 Multi-beam gamma density-meter

Gamma densitometer with single or multi beam has been used for a long time to measure the void fraction of two phase flow. Using multi beams was developed to supplement the single beam's shortcoming in inhomogeneous distribution of gas phase such as the stratified flow.

Recentely, research of this field is developing for two directions: improvement of signal quality and maximization of information production. To improve the signal quality, many radiation sources are now evaluating as noted by OOO [ ]. Also, to get more information with this sensor, many specific arrangement of beams are now considering. Using one gamma ray source, the number of detectors are increasing from one to many. Recentely, KAERI invent special arrangement to study the ECCS penetration to the downcomer of reactor. They located the gamma ray source in center of reactor core and made gamma ray spread for detectors mounted circularly to nuclear reactor outer wall.

2.2 Discrete Computer Tomography

As the main, even if not only, purpose is the detection of linear features we have selected a tool which is mostly suited to such objects, namely the Radon transform (RT, [16]), which is based on the parameterization of straight lines of the image domain, and on the evaluation of the integrals of the image along these straight lines. Although the RT enables the implementation of very effective detection algorithms, it does not provide by itself sufficient information for recognition purposes; it is then necessary to perform a further processing in order to properly identify each of the detected patterns.

If we have the intensity of gamma ray source and detector penetrating the medium, the absorption factor of the gamma ray in the medium through the particle trajectory could be defined as

$$-\int_L f(x,y)du = \ln(\frac{I}{I_0}) \tag{1}$$

where I_o is the gamma ray intensity of source and I is the detected gamma ray intensity penetrating through the medeium. We can get a function by projecting the ray propagation path as shown in Fig.2:

$$g = g(s,q) = \int_L f(x,y)du \quad -\infty < s < \infty, 0 \le q \le p \tag{2}$$

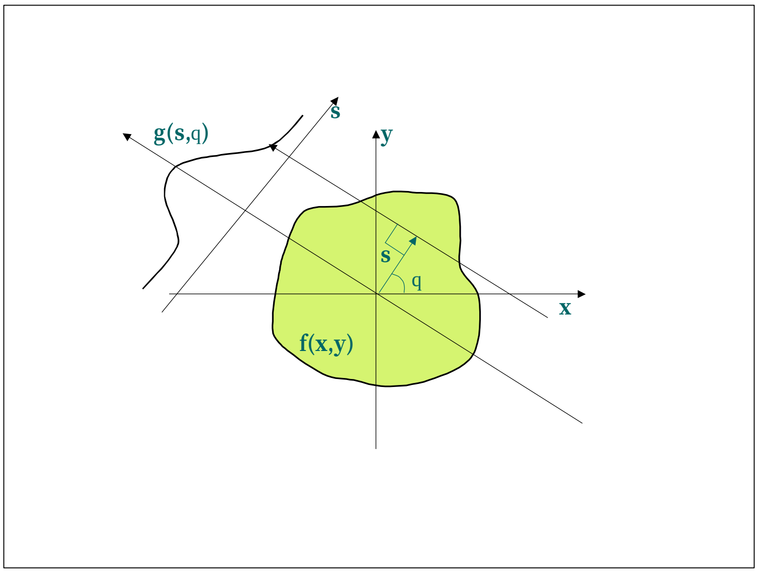


Fig.1 The coordiates of RT for f(x,y) and $g(s,\theta)$

where the path of ray can be represented as

$$du = \delta(x\cos\theta + y\sin\theta - s)dxdy \qquad (3)$$

The radon projection, Eq.(2), could be

$$g(s,\theta) = Rf = \int\int_{-\infty}^{\infty} f(x,y)\delta(x\cos\theta + y\sin\theta - s)dxdy \quad -\infty < s < \infty \;,\; 0 \le \theta \le \pi \qquad (4)$$

The back projection to find f(x,y) is made as

$$f^{*}(x,y) = Bg = \int_0^{\pi} g(s,\theta)d\theta = \int_0^{\pi} g(x\cos\theta + y\sin\theta, \theta)d\theta \qquad (5)$$

The image obatined by the back projection, $f^{*}(x,y)$, can be functioned to the origianl image, f(x,y), as:

$$f^{*}(x,y) = Bg = BRf(x,y) \qquad (6)$$

Therfore, the original image $f(x,y)$ could be reproduced by using the second order filter to the backprojected image $f^{*}(x,y)$:

$$f(x,y) = F_2^{-1}|\xi| F_2[Bg] \qquad (7)$$

where F_2 is the 2-dimensional Fourier transform operator), and corresposnding freuency response of $(x^2+y^2)^{-1/2}$ is $|\xi|$ where $|\xi| = \sqrt{\xi_1^2 + \xi_2^2}$.

Then the inverse radon transformation is

$$f(x,y) = \left(\frac{1}{2\pi^2}\right)\int_0^{\pi}\int_{-\infty}^{\infty} \frac{\left[\frac{\partial g(s,\theta)}{\partial s}\right]}{x\cos\theta + y\sin\theta - s} dsd\theta \quad \text{for } 0 \le \theta < \pi \;\; -\infty < s < \infty \qquad (8)$$

where $g(s,\theta) = Rf$.

Since the two-pahse flow to be anayied flows in thepipe, the cylindrical coordinate could simplify eqaution. Let us change x,y coordinate to the cylindrical coordinates of (r, Φ)

$$x = r\cos\Phi ,\;\; y = r\sin\phi, \text{ and } \; s = x\cos\theta + y\sin\theta = r\cos(\theta - \Phi) \qquad (9)$$

The tomography image could be obtained by finding f from g:

$$f^{*}(r,\phi) = \left(\frac{1}{2\pi^2}\right)\int_0^{\pi}\int_{-\infty}^{\infty} \frac{\left[\frac{\partial g(s,\theta)}{\partial s}\right]}{r\cos(\theta - \phi) - s} dsd\theta \qquad (10)$$

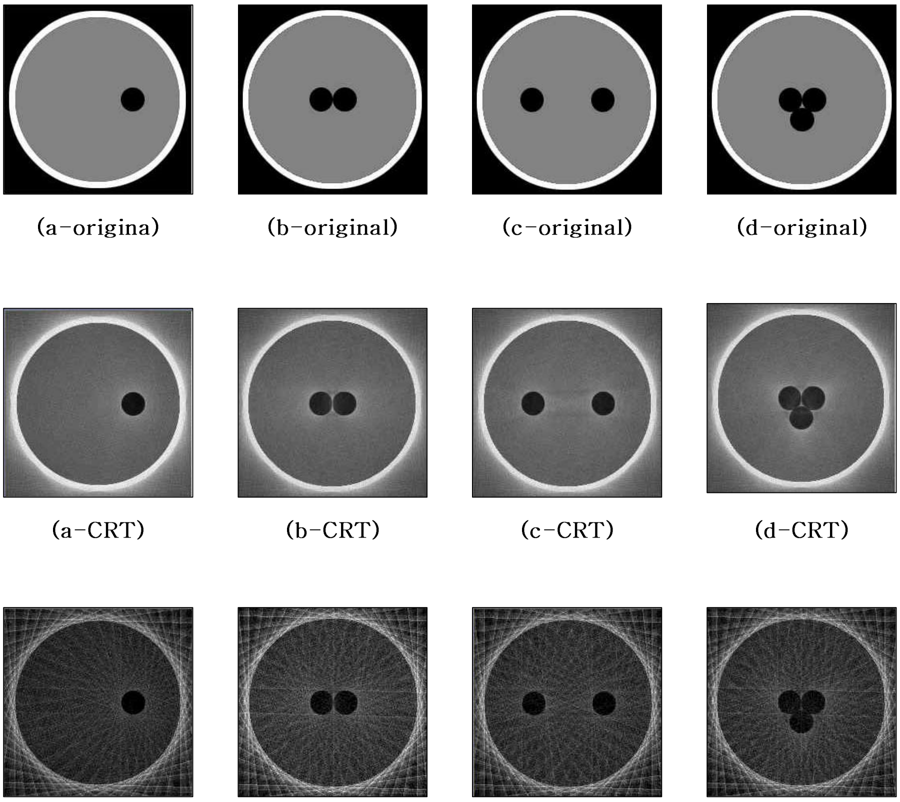
Inserting Eq.(10) into Eq.(7) produce the inverse RT for the cylindrical coordinates.

3. Results and Discussions

To examine applicability of the present discrete RT(DRT) to measurement of two-phase flow, three flow regimes are selected including bubbly flow, slug/annular flow, stratified flow. Wished to express various cases as long as possible, test samples are selected to know its predictability of size, location of suspected area.

3.1 Bubbly flow regime

The bubble identification could be one of good example to test the accuracy of the tomography method. In case of EIT, because the degree that small bubble changes electromagnetic field can be smaller than the background noise, it is very difficult to measure the size of bubble and identify each bubble in the bubble cluster. Four cases are selected to evaluated the performance of the present method by changing the number of bubbles and the distance between bubbles. As shown in Fig.2, the present DRT identify bubble well in size and location. However, to identify the inner polygon(d) made by surrounded three bubbles, DRT should equip very accurate edge detection algorithm and preprocessing scheme. Through this analysis, the present DRT with only 30 detectors confirmed that can be used to detect the stratified flow.



(a-origina) (b-original) (c-original) (d-original)

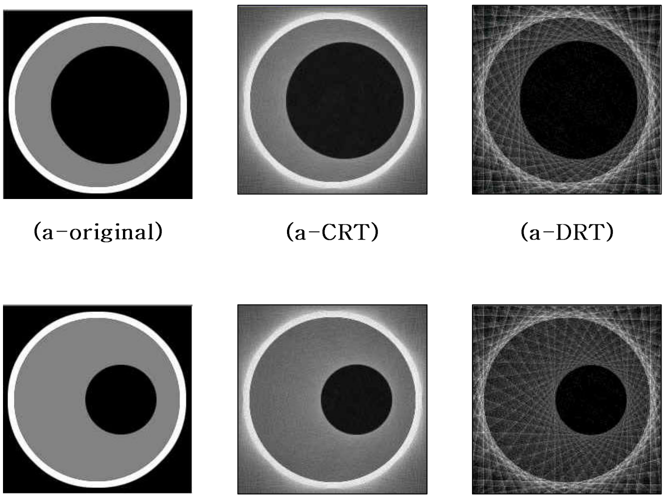
(a-CRT) (b-CRT) (c-CRT) (d-CRT)

(a-DRT) (b-DRT) (c-DRT) (d-DRT)

Fig. 2 The application of DRT to the bubbly flow

3.2 Slug/Annular flow regime

The annular boundary in the slug/annular flow is very important information in determining density of two-phase flow. Also, the various waves on the annular film surface are important parameters in understanding many fundamental phenomena such as flooding, enetrainment, etc. As shown in Fig.3, two representative samples are tried to check the capability of the present DRT. There are many lines tangent to the surface of the two-phase boundary, but the determination of two-phase bubble is not difficult in the heuristic observation. The size and location tested by the samples are well predicted. If we provide a proper image processing technique to the present scheme, the determination of the density of two-phase flow is very reasonable.



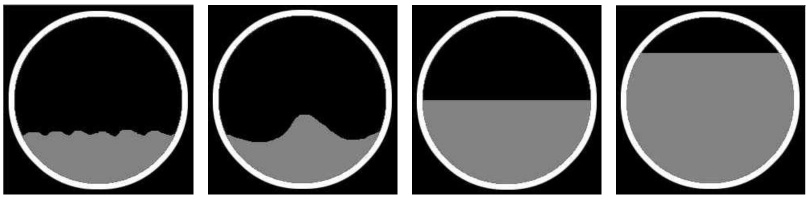
(a-original) (a-CRT) (a-DRT)

(b-original) (b-CRT) (b-DRT)

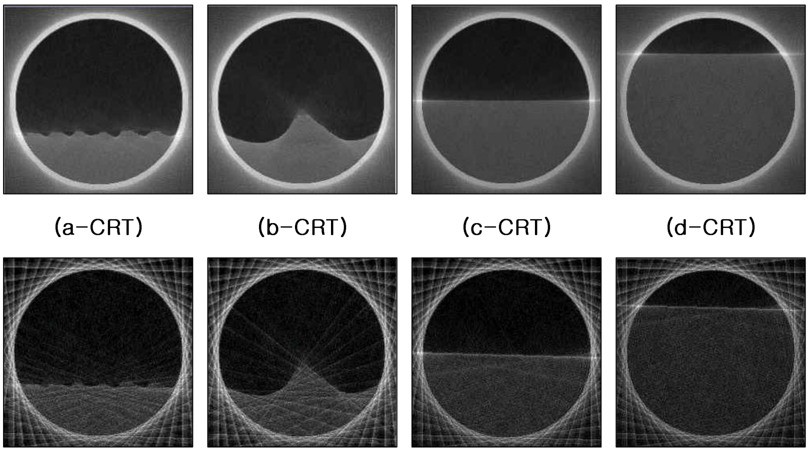
Fig.3 The application of DRT to the slug/annular flow

3.3 Stratified flow regime

The typical flow pattern in the horizontal two-phase flow is the stratified flow. Since its interifacial surface is even horizontally, the straight trajectory of the gamma particles should be precisely calibrated. Also, because of the area that the gamma ray could not touch, multi-beam gamma ray method is used. Four cases are selected to evaluated the performance of the present method. As shown in Fig.4, the small ripples at the interface are well detected by CRT, but they are distorted in the DRT. But the water level is well predicted by both methods. Also, the artificial solitary wave also well detected by both methods. The sharpe peak got cloudy which is the typical results of RT. Recent researches are focus on this problem. The Wavelet filter was reported to identify the sharpe edge in the image[ ]. The images of (c) and (d) represents both RT detect the water level and its perfectly plat plain. As expected, the wavy interface(a,b) shows less bright spots at the wall that the two-phase interface touches than the perfect plat interface(c,d). Through this analysis, the present DRT with only 30 detectors confirmed that can be used to detect the stratified flow.



(a-original) (b-original) (c-original) (d-original)



(a-CRT) (b-CRT) (c-CRT) (d-CRT)

(a-DRT) (b-DRT) (c-DRT) (d-DRT)

Fig. 4, The evaluation of CRT and DRT for the various stratified flow

4. Conclusions

Through the present study, we examine the applicability of the radon conversion with discrete signals from the multi beam gamma densitometer to measure the cross sectional distribution of void in two phase flow. Noise increases as the number of beams reduced. But it is not degree to dubiously lose boundary of bubbles stick near. It was found that the we could measure the density enough by 30 discrete beams for various flow regimes such as bubbly flow, annular flow, and staratified flow. Precision of this method was confirmed in expressing well the boundary of near bubbles and the small ripples on the surface of stratified flow, etc. Therefore, it is expected to augment greatly accuracy when apply modern image processing techniques in this result.

This research did role favor that reduce number of radiation detector, but have problem that must increase radiation source's number. Further works are required for the measurement of void fraction to develop a new transformation method that can use single radiation source and minimum detectors. Also, it is needed filter improvement with Wavelet and development of the post image processing procedure.

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Appendix The application of the discrete RT to KAERI arrangement

$$\ln\left(\frac{I}{I_o}\right) = -\int_{u_1}^{u_2} f(x,y)\,du$$

SInce the direction of gamma ray propagation and the integral path are different,

$$\ln\left(\frac{I_1}{I_o}\right) = -\left(\boldsymbol{u}_{ray}\cdot\boldsymbol{u}_{int}\right)\int_{u_o}^{u_1} f(x,y)\,du = \int_{u_o}^{u_1} f(x,y)\,du$$

$$\ln\left(\frac{I_2}{I_o}\right) = -\left(\boldsymbol{u}_{ray}\cdot\boldsymbol{u}_{int}\right)\int_{u_o}^{u_2} f(x,y)\,du = -\int_{u_o}^{u_2} f(x,y)\,du$$

Therefore

$$-\int_{u_1}^{u_2} f(x,y)\,du = -\int_{u_0}^{u_2} f(x,y)\,du - \int_{u_1}^{u_o} f(x,y)\,du$$

$$-\int_{u_1}^{u_2} f(x,y)\,du == \ln\left(\frac{I_2}{I_o}\right) + \ln\left(\frac{I_1}{I_o}\right) = \ln\left(\frac{I_1 I_2}{I_o^2}\right)$$