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# Proper Orthogonal Decomposition as a technique for identifying multiphase flow regime based on Electrical Impedance Tomography

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## ABSTRACT

*Collecting very large amount of data from experimental measurement is a common practice in almost every scientific domain. There is a great need to have specific techniques capable of extracting synthetic information, which is essential to understand and model the specific phenomena. The Proper Orthogonal Decomposition (POD) is one of the most powerful data-analysis methods for multivariate and nonlinear phenomena. Generally, POD is a procedure that takes a given collection of input experimental or numerical data and creates an orthogonal basis constituted by functions estimated as the solutions of an integral eigenvalue problem known as a Fredholm equation. By utilising POD to identify flow structure in horizontal pipeline, specially, for slag, plug and wavy stratified air-water flow regimes, this paper proposes a novel approach, in which POD technique extends the current evaluation procedure of Electrical Impedance Tomography applied on air-water flow measurement. This extension is provided by implementation of the POD as an identifier of typical horizontal multiphase flow regimes. The POD snapshot matrices are reconstructed for EIT measurement domain and specific flow conditions. Direct POD method introduced by Lumley is applied. It is expected that this study may provide new knowledge on two phase flow dynamics in a horizontal pipeline and supportive information for further prediction of multiphase flow regime.*

**Keywords** Proper orthogonal decomposition, Two phase flow, Horizontal flow regime, Electrical Impedance Tomography

## 1. INTRODUCTION

Considering a gas-liquid two phase flow, the liquid and gas are regarded as the continuous and dispersed phases respectively. Gas-liquid flows are commonly observed in many industrial processes such as oil and gas, chemical, pharmaceutical and nuclear industries. The relative distribution of the gas and liquid phases can take many different configurations depending on the process conditions, such as the flow rates of the gas and liquid. The configuration of the gas and liquid phases is known as the flow regime (Wallis, 1969). The flow regime describes the pattern of the inner structure of the flow and important hydrodynamic features such as volume fraction, phase and velocity distributions. Two phase flow regimes are often determined subjectively using direct methods such as the eyeballing method, high speed photography method and the radial attenuation method (Dong, Liu, Deng, Xu, & Xu, 2001). Empirical flow regime maps such as the Baker chart (Tilton, 2008) are commonly used for approximate and rapid identification of the flow regime under specific operating conditions. However, due to their approximate and subjective nature these techniques are not able to identify the prevalent multiphase flow regime with the required degree of accuracy. Statistical analysis of the signal has also been used for identification of flow regimes (Faraj *et al.,* 2015). The prediction of flow patterns for fully developed gas-liquid flows typically employ mechanistic models that use different pressure drop and void fraction estimation procedures for each flow pattern. Accurate prediction of heat transfer, void fraction and pressure drop in gas-liquid flow is important in the design and optimisation of the unit operations dealing with such systems (Jassim, Newell, & Chato, 2006). Therefore different flow regimes require specific modelling equations to predict their respective transfer properties. Hence in order to produce a reliable design for a multiphase system it is imperative to be able to accurately determine the prevalent flow regime. In the recognition of the prevalent flow pattern one must consider the relative quantities of the phases and the topology of their interfaces (Tilton, 2008). In two phase flow many other flow regimes are possible such as; stratified flow, bubbly flow, slug flow, plug flow and annular flow among others. The flow regime that is active depends on a number of factors; the fluid transport and material properties, flow rates, flow direction (co-current or counter-current), the shape and size of the conduit and the orientation (horizontal or vertical) (Kleinstreuer, 2003). Considering the orientation of the flow, due to differences in the densities of the phases, vertical flow patterns are different to those obtained in horizontal flow. An intrinsic difference

between the two orientations is that horizontal flow patterns are generally not axisymmetric. Because of this the measurement of gas/liquid multiphase flow in horizontal pipes is inherently more difficult than that in vertical pipes due to the flow regimes experienced in the former configuration. Therefore, this study focuses on horizontal gas-liquid flow in pipes. Typical flow regimes obtained in horizontal gas-liquid multiphase flows are stratified flow, wavy stratified flow, slug flow, plug flow, bubble flow and annular flow (Ma, Zheng, Xu, Liu, & Wu, 2001). In the bubble flow regime the bubbles are located near the top of the pipe due to buoyancy effects. Increasing the superficial velocity of the gas will promote the coalescence of the bubbles resulting in plug flow. A further increase in the superficial gas velocity will cause the gas plugs to form a continuous layer of gas above liquid resulting in a smooth interface between the gas and liquid which is termed stratified flow. In this flow regime the gas will move at a higher velocity than the liquid due to the lower viscosity and density of the gas phase. Once again increasing the superficial velocity of the gas will increase the interfacial stress and create wave flow. A further increase in the gas flow rate will result in waves that are able to bridge the top of the pipe and hence produce large slugs of air in the top section of the pipe and this is known as slug flow. At extremely high superficial gas velocities annular flow is achieved whereby a thin liquid film flows along the pipe wall surrounding a centralised core of gas. A further increase in the gas flow rate will result in the formation of spray flow where the liquid phase is distributed as small droplets within the gas phase (Holland & Bragg, 1995).
In order to better understand the fluid dynamic nature of Gas-liquid multiphase flows this paper focuses on flow regimes and pressure drop identification using approaches based on Computational Fluid Dynamics. Physical, mathematical and numerical models of horizontal flow regimes are developed and presented.

## 2. APPROACH

The intention of developing a method for recognition of flow regime using decomposition mathematical technique comes from the fact that each regime is characterised by typical dynamic behaviour. To recognise the flow dynamic structures, means indeed the recognition of the prevalent regime moreover indicates the actual flow conditions of the monitored area.
The main aim of the present study is to develop a method of flow regime recognition, which is based on Proper orthogonal decomposition (POD). Additionally, the basic functions determined by experimental investigation serve to the database and numerical model validation. The schematic diagram of the concept is illustrated in Figure 1. The highlighted blocks in the scheme present the current state of the research and the contribution to the complex method.

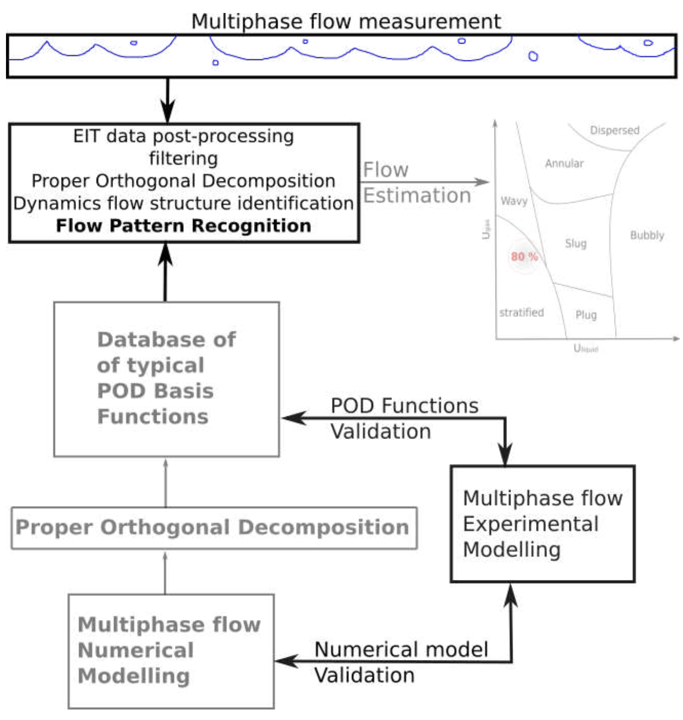



**Figure 1: Scheme of Flow pattern recognition based on POD**

From a mathematical point of view, the Proper Orthogonal Decomposition is a transformation with a diagonal matrix *U(**x**,t)* and brings it to a canonical form. The mathematical concept of POD is based on the spectral theory of compact, self adjoins operations (Courant, Hilbert 1953). The vector-value function approximation, the conductivity or concentration in this study, over domain of interest, is supposed as a finite sum in the variables-separated form:

$$U_m(\vec{x},t) = \sum_{j=1}^{M} a_j(\vec{x})\varphi_j(t) \tag{1}$$

The experimental data uses direct POD approach, which is developed by (Lumley, 1967). In this case the average is temporal and evaluated as an ensemble average, based on the assumptions of stationary and ergodicity. On the other hand, the variable *U(**x**,t)* is assimilated to the space variable ***x***=*(x,y,z)* defined over the domain of interest (two measurement ERT planes). In order to estimate the set of POD basis functions, Python parallel library MODRED (Belson, 2013) is used. The fundamental characteristics of the calculation procedure are as follow:

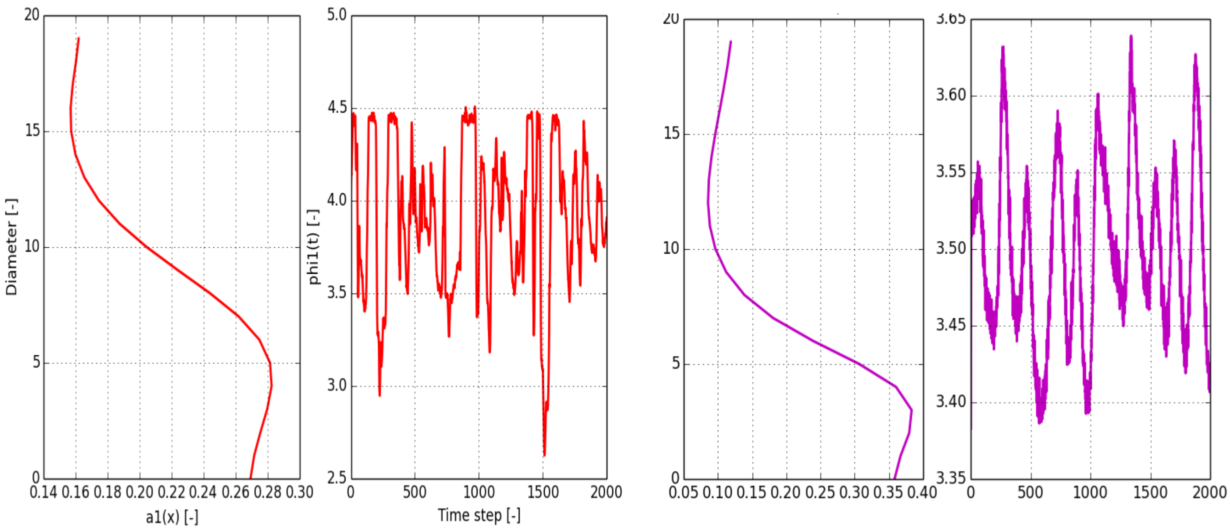
- Collect and store vectors $u_i$ (each cells of tomograms in each time $i = 1 \ldots m_t$),
- Compute each entry of the correlation matrix $H$ via $[H]_{i,j} = \langle u_i , u_j \rangle$,
- Compute the eigenvalues and eigenvectors of correlation matrix,
- Sort the eigenvalues and corresponding eigenvectors in descending order,
- Select the number of modes $M$,
- Compute the matrix $A(a_j)$,
- Construct modes $\phi_j$ individually via (2)

$$\varphi_j(t) = \sum_{i=1}^{m_t} u_i(\vec{x}) a_{i,j}^T(\vec{x}) \tag{2}$$

The different number of modes is tested, $M \in \langle 3 - 20 \rangle$. The reconstructed image shows the dominant role of the first few modes. POD can be applied for flow regime recognition using reduced number of modes (3 modes), unlike the identification of fluid dynamics behaviour, in in which higher number of modes is required.

## 3. RESULTS AND DISCUSSION

Different flow regimes can be characterised through different structure of flow dynamics. In other words, each mode of POD can be used to represent the prevalent flow regime within the pipeline, as shown in Figure 2. The estimation of the first dominant basic functions enables, with certain probability, the recognition of the flow regime based on the acquired signal from multiphase flow measurement. Figure 3 shows the comparison between the flow image reconstructed using EIT with that of POD. The EIT-based reconstructed image is shown in terms of stacked concentration tomogram. It is quite apparent that, the EIT technique can be utilised for validation of the results generated from the POD.




a) Plug flow regime b) stratified flow regime

**Figure 2: Characteristics POD Basis functions, 1st mode**

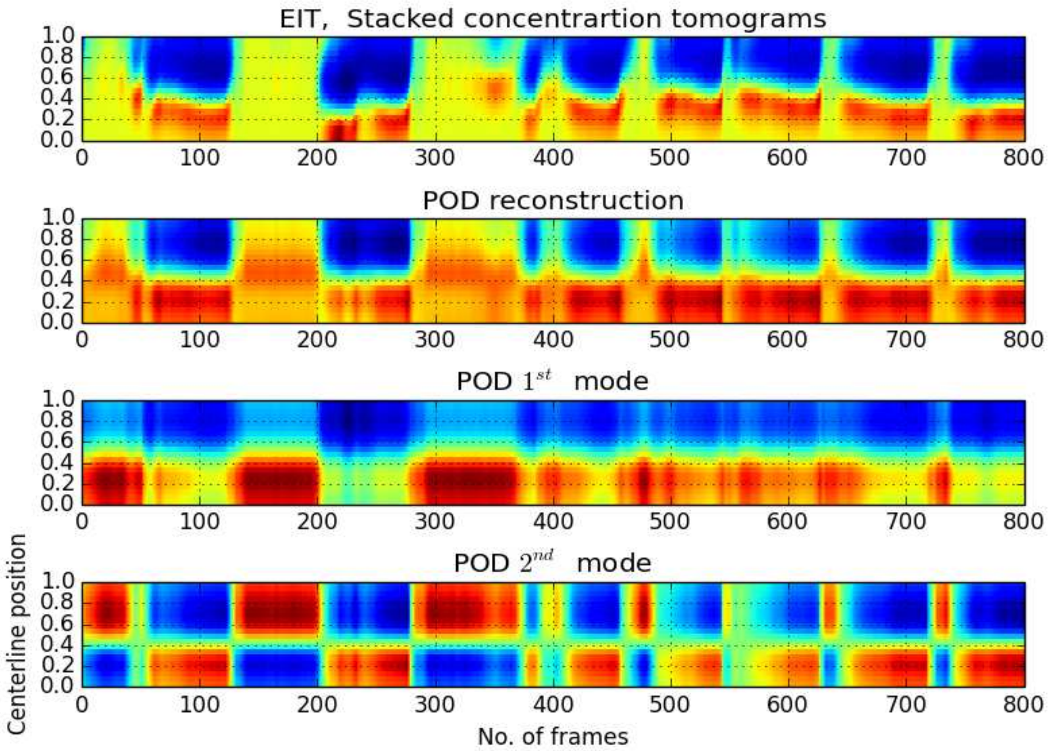



**Figure 3: Comparison of the POD-based reconstructed image with that of the EIT for horizontal plug flow**

Figure 2. demonstrate the extraction of flow information which characterise the EIT signal from dynamics point of view, and Figure 3 illustrate the capability of original image reconstruction according extracted basis function, with certain accuracy . Both attributes of POD techniques will be utilised for further flow regime recognition based on the developed reduce-order model.

## 4. CONCLUSIONS

Two-phase gas-liquid flow regime recognition using any decomposition technique could be promising methods for EIT data post-processing. The proposed method is based on typical fluid dynamic structure and instability recognition on the flow measurement, which is based on POD. The application of the method is based upon the database of typical basis functions. The database could be developed by multiphase flow CFD modelling and implementing the theory of multiphase flow instability. The proposed method is used to validate the numerical models based on Large eddied simulation or Direct simulation approaches (Triggvason *et al.,* 2005). Also, to test and validate the established databases of typical basis functions for horizontal gas-liquid flow, reported elsewhere (Polansky *et al.,* 2015).

A part of the present procedure is signal filtering of HW noise and noise induced by EIT signal reconstruction algorithm. In principle, this filtering could be as part of the POD methods. However, this can work quite well if the estimated different POD modes are assigned for different types of dynamic behaviour. In other words, i.e. the external noise is clearly distinguished from fluid dynamics phenomena, otherwise, the filtering has to be performed separately from POD.

The accuracy of flow regime identification is depends on the frequency of the data obtained from the of EIT. This implies that, the flow regime recognition can not be carried out on-line according to the principle of the statistical decomposition techniques. The speed of flow regime recognition depends on the number of frames acquired from the EIT, and this number of the frames should take into account all flow dynamic features related to the active flow regime. Nevertheless, the method returns the preliminary information on regime identification, and the higher the number of frames is, the more accurate identification of the regime can be achieved. Further increase the number of EIT measured frames will apparently increase the time length of POD evaluation.

The different POD approaches, direct versus Snapshot method, optimal time of evaluating record, total number of evaluated POD mode, optimal size of snapshot matrix, the number of modes used for estimation process, signal filtering, and dependencies of estimation accuracy of all mentioned parameters, is the subject of the present and complex future study.

## 5. ACKNOWLEDGEMENTS

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