Jurnal Teknologi, 55 (Sains & Kej.) Keluaran Khas (2), Ogos 2011: 87–99

OPTIMIZATION OF ELECTRICAL CAPACITANCE TOMOGRAPHY SENSOR USING DESIGN OF EXPERIMENT METHOD

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Abstract. This paper discusses the Design of Experiment (DOE) method to design an optimum Electrical Capacitance Tomography (ECT) sensor for gas-oil flows. The method has focused mainly on eliminating overshoots and undershoots in normalized ECT data. The DOE technique employed was an implementation of a 2^k factorial design. ECT data based on ECT sensor parameters were used to evaluate the interaction among factors or inputs (i.e. ECT parameters) and the responses or outputs (i.e. normalized ECT data overshoot or undershoot) The results demonstrate the feasibility of using DOE to determine the interaction or influence of sensor parameters on the severity of normalized ECT data overshoots and undershoots and to facilitate the design of the most optimum ECT sensor for a particular application.

Keywords: Design of experiment; electrical capacitance tomography; sensor optimization

Abstrak. Kertas ini membincangkan kaedah reka bentuk uji kaji untuk menghasilkan penderia Tomografi Kemuatan Elektrik (TKE) yang optimum bagi aplikasi gas dan minyak. Fokus kaedah ini adalah untuk mengurangkan kesan data TKE ternormal yang terlajak dan lajak bawah. Kaedah reka bentuk uji kaji yang digunakan adalah jenis reka bentuk faktorial 2^k. Data TKE berdasarkan parameter penderia digunakan untuk menilai hubungan antara faktor atau masukan (iaitu parameter TKE) dan sambutan atau keluaran (iaitu data TKE ternormal yang terlajak dan lajak bawah). Hasil uji kaji menunjukkan bahawa teknik reka bentuk uji kaji dapat digunakan untuk menentukan hubungan atau pengaruh parameter pengesan terhadap kesan data TKE ternormal yang terlajak dan lajak bawah bagi menghasilkan penderia TKE yang optimum.

Kata kunci: Reka bentuk uji kaji; tomografi kemuatan elektrik; pengoptimuman penderia

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1.0 INTRODUCTION

Electrical Capacitance Tomography (ECT) is a non-intrusive, non-destructive image reconstruction technique used in industrial processes to obtain information about the contents of closed pipes or vessels by measuring variations in the dielectric property of materials inside the vessel (Kim *et al.*, 2007). Capacitance values obtained from an ECT sensor typically are very small, in the range of 0.01pF to 1pF (Yang *et al.,* 2003). Hence, optimum sizes of ECT parameters play important roles in eliminating large overshoots (i.e. normalized capacitance values larger than the upper) and undershoots (i.e. normalized capacitance values smaller than the lower bound), leading to high capacitance sensitivity.

Figure 1 shows a schematic diagram of an ECT sensor. R1 is the inner pipe radius measured from the centre to the inner wall of the pipe. R2 is the outer pipe radius from the centre to the outer wall of the pipe. R3 is the radius of the pipe screen from the centre to the outer screen. Until now, no proper method has been used to determine an optimum ECT sensor for a particular application. Although the size of electrodes used in designing ECT sensor is application dependent, they have so far been chosen based on a trial-and-error method that is time intensive. When this approach is used, some important parameters influencing sensor sensitivity may be overlooked.

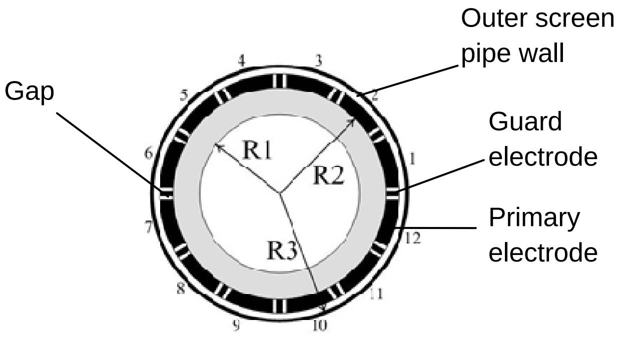

Figure 1 2-D model of ECT sensor. The numbers refer to the sensing electrodes

Many parameters influence the quality and effectiveness of an ECT sensor. The parameters that play important roles in ECT sensor design include (William and Beck, 1995; Xie *et al.,* 1992):

- The thickness and type of material in the pipe wall between the electrodes and the sensing zone (the insulating lining),
- The thickness and material of the pipe wall separating the electrodes and the screen,
- The size of the electrodes,
- The guarding used, i.e. radial guards or plane axial guards, and whether end guards are used.
- The gap size between the primary electrodes and the guards, and the dimensions of the guarding electrodes.

As these parameters are inter-related, an optimum ECT sensor cannot be obtained using one-factor-at-a-time approach (Osman-Ali *et al.*, 2008) because the interaction of the parameters influence overshoots and undershoots. Instead, various DOE methods can be used for the purpose, depending on the applications and the characteristics to be analyzed.

DOE is a process of planning an experiment, so that appropriate data for statistical analysis are collected (Montgomery, 2005). Conventionally, DOE techniques have been used in physical experiments such as agriculture field experiments (Kuentz, 2003) and controlled clinical trials (Ko *et al.*, 2003). Computer simulated experiments differ from the physical experiments in that they use computer codes to generate data and create virtual environments to simulate the experiments of interest (Wang and Halpin, 2004). Although many DOE techniques have been developed with physical experiments in mind, they can be adapted fairly easily for use in computer simulation experiments as well (Kelton and Barton, 2003).

This paper aims to introduce DOE as a method to determine significant ECT parameters in producing an optimized ECT sensor. The initial assumption made is that all the parameters have some influence on the performance of the sensor. Then, DOE method is employed to analyze which parameter significantly influence the sensitivity of an ECT sensor design. This process should facilitate the task of designing an ECT sensor in the future.

2.0 DOE METHOD

The present study describes the implementation of a DOE technique based on the 2^k factorial design method for analyzing the process of designing an optimum ECT sensor to determine the most significant parameter which could eliminate large over- and under-shootings. Factorial design is one of the most common methods in DOE which has been widely used in experiments involving several factors, where it is necessary to study the joint effects of factors on responses (Montgomery, 2001). There are several levels in the factorial design method. The use of each level depends on the application and the type of experiment. The level of factorial design employed in this work is 2^k because it is particularly useful in the early stage of a study that requires investigations of many potentially important factors. The 2^k design provides the smallest number of runs in which k factors can be studied in a complete factorial design. The main effects of factors and interactions between them can be estimated when performing experimental design. The main effect measures the effect of each individual factor on a response. By assigning two opposite levels; high (indicated using plus sign, '+') and low (indicated using a minus sign, '-') to each factor, the main effect of each factor can be estimated. This assessment is made by taking the difference between the averages of responses for all observations at the high level of a factor, say A, and the average of responses for all the observations at the low level of A.

In practice, the size and material of pipe onto which an ECT sensor is attached are application dependent. The pipe thickness and also inner radius must meet the specified requirements for the application. Hence the material, thickness of pipe and also its radius are held constant during the evaluation. In the experiment, R1 was set to 50 mm, R2 to 52 mm and R3 was varied for evaluation.

All of the analyses were done with data generated from an ECT simulator (Spink, 1996). Three parameters considered for the analyses are the angular angle of the primary electrodes, **E**, the angular angle of the gap between electrodes and also the guard electrodes, **G**, and the radius of the pipe screen, **R**. Each of these factors was evaluated to determine the most significant factor(s) for an ECT sensor and also to evaluate their interactions. Table 1 summarizes the factors for a 2^3 factorial design. The first step was to identify a design matrix that is suitable for the study. A design matrix is a matrix description of an experiment that is useful for constructing and analyzing experiments. The matrix contains of a maximum and a minimum value for each factor. High level, +1, is the maximum value and low level, -1, is the minimum value for the factors.

Table 1 Factors for k=3 factorial design

Factors	**High (+1) Level**	**Low (-1) Level**
Electrode, (E)	21°	10°
Gap, (G)	3.5°	1.5°
R3, (R)	63 mm	55 mm

Table 2 presents a design matrix for an experiment that uses the highest and lowest normalized capacitance values for an ECT sensor. The simulation study is deterministic in the sense that the same set of inputs will always generate the same results (Wang and Halpin, 2004). Thus, replication is not necessary.

Table 2 Design matrix and responses for the k=3 design

ECT Sensor Parameters		
Electrode, (E)	**Gap, (G)**	**R3, (R)**
-1	-1	-1
1	-1	-1
-1	1	-1
1	1	-1
-1	-1	1
1	-1	1
-1	1	1
1	1	1

ECT sensor design is flow-regime dependent. As ECT technique has been widely used to analyze flows, this work focuses on gas-oil flows, involving commonly formed flow regimes as depicted in Figure 2. Each of the flow regimes was varied into 14 to 15 different sizes of oil droplets and gas bubbles to produce variations in the flow patterns.

Using the same design responses for each flow regime, the undershoot and overshoots were determined from the normalized capacitance values based on the equation (Yang and Byars, 1999),

$$N_{ij} = \frac{\dfrac{1}{C_{\mathrm{ij(p)}}} - \dfrac{1}{C_{\mathrm{ij(e)}}}}{\dfrac{1}{C_{\mathrm{ij(f)}}} - \dfrac{1}{C_{\mathrm{ij(e)}}}} \tag{1}$$

where N_{ij} is the normalized capacitance for electrode pair *i* and *j*, $C_{ij(e)}$ is the capacitance value when the pipe is full of gas or material with lower permittivity, $C_{ij(f)}$ is the capacitance when the pipe is full of oil or other higher permittivity material, and $C_{ij(p)}$ is the measured capacitance for electrode pair *i* and *j*. Based on equation (1), when the sensor is full of lower permittivity material, N_{ij} is 0 and when it is full of higher permittivity material, N_{ij} is 1. From equation (1), overshoot occurs when the normalized capacitance exceeds value 1 and undershoot occurs when a normalized capacitance is lower than 0. If the N_{ij} value is larger than 1 (i.e. overshoot) or smaller than 0 (i.e. undershoot), then it will also influence the sensitivity matrix of an ECT sensor, and may produce low fidelity reconstructed images of material distribution.

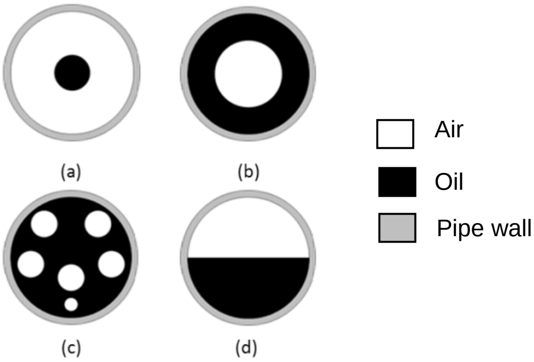

Figure 2 Commonly formed flow regimes (a) core, (b) annular, (c) bubbles and (d) stratified

The average over- and under-shooting for each flow regime variation was calculated and used as the response in the experiment. The shooting value is the sum of the average under-shooting with the average over-shooting and was calculated by using,

$$shooting = \frac{1}{n}\sum_{i=1}^{n} os_i + \frac{1}{m}\sum_{i=1}^{m} \left|us_i\right| \tag{2}$$

where *os* is the overshoot value, *us* is the undershoot value, *n* is the number of over-shooting and *m* is the number of under-shooting.

Each flow regime has different characteristics that may influence the accuracy of the DOE results. In other words, the shooting pattern for a stratified flow regime will not be the same as that for a core flow regime. This problem can be solved by introducing a blocking method in DOE (Montgomery, 2005). Blocking is a design technique that is used to systematically eliminate known and controllable nuisance factor among of treatments by dividing the combinations of factors in Table 2 into blocks.

The next step was to create a normal probability plot of effects to identify the significant effects. The effect values show how changing the settings of a factor change the response, and are treated as positive numbers for comparison purpose. The larger the effect value, the higher the influence on the response or output and vice versa. Typically, the significant effects do not lie along the same line in the normal probability plot. In other words, effects that do not lie along the same line have a greater probability of being significant. Refer to Montgomery (2005) for a detailed discussion on effect equations for each model effect.

3.0 RESULTS AND DISCUSSION

Discussion on the analysis of the results is based on a normal probability plot for flow regime shootings, the factor-response effects, and the factor combinations. An initial experiment was done with the one-factor-at-time method (Figure 3). The size of **E** was varied while **G** and **R** were held constant. The objective of this experiment was to determine which flow regime gives significant shooting values. Initially, G 1.5°, R 55 mm and E was varied from 7° to 25.4°in increments of 0.8°. Only stratified and core flow regimes give significant shooting changes. The annular and bubble flow regimes give only small shooting with no large changes when **E** is varied. Based on the results of this initial experiment, only stratified and core flow regimes were considered in the DOE experiment.

Since different flow regimes can become a nuisance factor in the factorial design experiment, the blocking method was introduced, which made modification to the previous design matrix (refer to Table 2) possible. The modified design matrix is shown in Table 3. Blocks 1 and 2 in Table 3 can be either stratified or core flow regime. The shooting values in Table 4 for both flow regimes were obtained from the ECT simulator based on the blocking method design matrix of Table 3. Each row in the table represents a combination of factors. For example **E** is a condition in which only factor **E** is at the maximum value while other factors are at the minimum value and **EG** is a condition under which factors **E** and **G** are at the maximum value and all of the other factors are at minimum values.

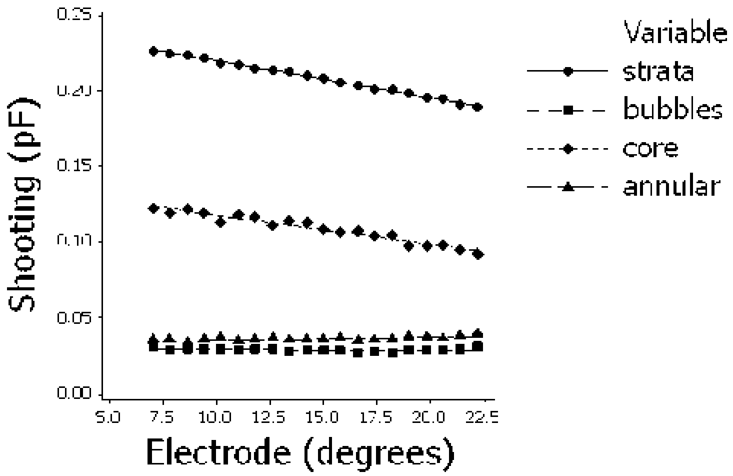

Figure 3 Shootings for stratified, bubble, core and annular flow regimes with electrode size, varied from 7° to 25.4°

From Figure 4, at 99% confidence level, only factor **E** seems significant. Thus, only factor **E** is expected to have influence towards the shooting of ECT values. Further evaluation of factor **E** was conducted with a main effect graph as shown in Figure 5. The **E** minimum value (-1) produced a higher shooting value than maximum value (1). Thus larger electrode sizes result in lower shooting values than do smaller electrodes. Based on these results, an ECT sensor should have large electrodes to reduce the shooting value. Since only factor **E** is significant, other factors need not be emphasized when designing an ECT sensor. However, further analysis on the interaction between factors **G** and **R** is also important for an ECT sensor design. The results are illustrated in Figure 6.

Table 3 Design matrix and responses for k=3 design with blocking

Blocks	**ECT sensor parameter factors**			**Responses**
	Electrode, (E)	**Gap, (G)**	**R3, (R)**	**Shooting values**
1	-1	-1	-1	0.2180
1	1	1	-1	0.1900
1	1	-1	1	0.1870
1	-1	1	1	0.2170
2	1	-1	-1	0.0935
2	-1	1	-1	0.1167
2	-1	-1	1	0.1168
2	1	1	1	0.0887

Table 4 Effect estimates for the blocked factorial design experiment

Model Term	**Effect estimate**
E	-0.02733
G	-0.00074
EG	-0.00017
R	-0.00217
ER	-0.00174
GR	0.001675
Block (EGR)	0.066046

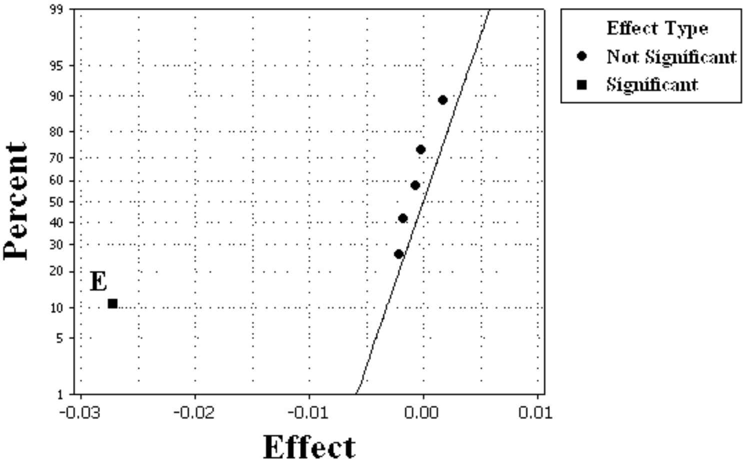

Figure 4 Normal probability plot for the data in Table 4

Shooting was lowest when **R** is high and **G** is low indicating that a thick screen with a small gap reduces the shooting for an ECT sensor. Since neither **G** nor **R** by itself is significant, changing the size slightly changes the shooting value. However, designing an ECT sensor based on Figure 6, should help to reduce the total shooting value.

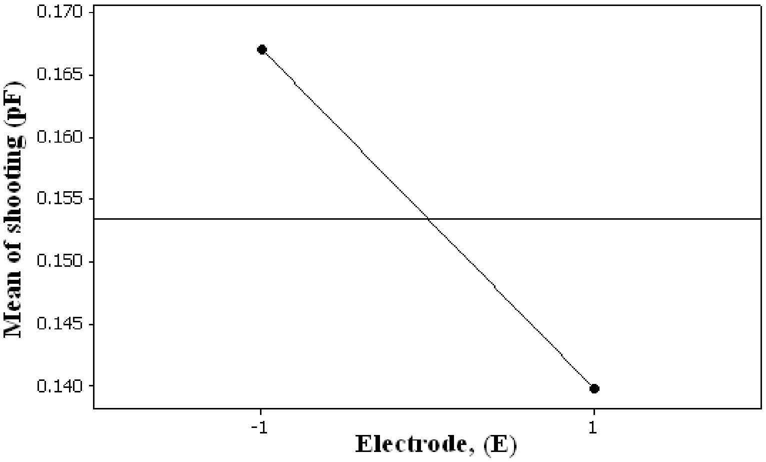

Figure 5 Main effect plot of E for shooting values

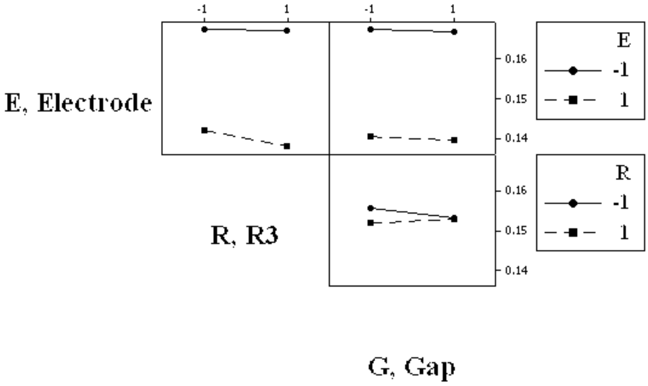

Figure 6 Interaction effect plot of E, G and R for shooting values

Based on the results obtained with the DOE technique, it can be concluded that an ECT sensor should have large electrodes and a thick screen with gaps as small as possible. These results are consistent with the findings of Xie *et al.* (1992), using a trial-and-error approach. For this investigation, the optimal parameter values for an ECT sensor R1=50 mm, R2=53 mm, R3=65 mm, E=26° , G=1° and guard electrode = 2°.

5.0 CONCLUSION

DOE method was proposed to effectively identify the interaction amongst ECT sensor parameters towards designing an optimum ECT sensor. Analysis of DOE results showed that electrode size is the most significant factor that must be considered when designing an ECT sensor. The optimum design requires large electrode size to ensure high sensitivity. Apart from that, the gap between primary electrodes must be as small as possible and the screen must be thick to maintain the sensor's shooting values to an acceptably small value. In addition, DOE helps researchers towards understanding the ECT sensor's characteristic.

ACKNOWLEDGEMENTS

The authors wish to thank MOHE for the financial support under the Fundamental Research Grant Scheme (FRGS) No: 203/PELECT/6071148, and MOSTI for the financial support under E-Science Fund Grant project NO: 03-01-05-SF0134.

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