TSSA Journal of Tomography System & Sensors Application Vol.4, Issue 1, March 2021
www.tssa.com.my e-ISSN: 636-9133

A Finite Element Method using COMSOL on ERT Applying Metal Wall Pipe: Effect on the Potential Distribution and Current Streamline

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Accepted 3 March 2021, available online 31 March 2021

ABSTRACT

This paper presents the effect on potential distributions and current streamlines for Electrical Resistance Tomography (ERT) applying metal wall pipe. A conducting boundary approach was applied in the measurement part of the research and COMSOL Multiphysics software has been applied in this work to solve the forward problem of the system. Sixteen electrodes with gold plated material as the conducting surface and FR4 as the insulating material were implemented as the sensing plate in the research. The simulations showed that the sensing field will be deflected based on the conductivity distribution within its sensing region. The electrical potential of the system also varied accordingly.

Keywords: Electrical resistance tomography, Conducting boundary strategy, Finite element method, COMSOL.

1. Introduction

Extracting information from industrial pipelines is important when monitoring the process to ensure it meets certain standards or requirements. Tomography seems to be one of the applications that accommodate this environment well. The ERT system has been used in numerous applications in process tomography. Accurate modelling of the measurements and prior information about the target distribution is required to solve the inverse problem for image reconstruction in ERT [1]. The ERT model which is the forward problem in ERT relates to the dependency between the conductivity distribution and the boundary voltages [2]. The sensitivity distribution of a homogeneous conductivity medium can be acquired by solving the forward model, using both analytical and numerical methods. Because it is difficult to obtain analytical solutions of the equation, numerical solvers, namely finite element methods (FEM), are preferable and are the most commonly used method for solving the forward problem. COMSOL Multiphysics 4.2 was utilised in this work to solve the forward problem of an ERT system of a conducting vessel pipe.

COMSOL Multiphysics software is one of the finite element methods and is a powerful interactive environment for modelling and solving all types of scientific and engineering problems. It offers a complete and integrated modelling environment for creating, analysing, and visualising Multiphysics models. Internally, the software compiles a set of equations representing the entire model. The model was created by defining relevant physical quantities such as material properties, loads, constraints, sources, and fluxes, rather than outlining the underlying equations [3].

Most of the vessels and pipelines in industry are made from conducting material which is metal. However, relatively few empirical research studies have investigated ERT systems for a metal wall application [4-10]. These researchers did not discuss thoroughly on the simulation study applying conducting boundary strategy. This paper aims to investigate the effect on potential distributions and current streamlines for sixteen sensor electrodes attached on a metal pipe wall using the finite element method software, COMSOL.

2. Principles of ERT

The basic principle underlying ERT is that the conductivity of different media is distinct. Thus, the medium distribution of the measured area can be identified if the conductivity or resistance distribution of the sensing field is obtained [11,12]. The operation of an ERT system provides the sensing field with an exciting current (or voltage) and measures the potential difference (or current) via electrodes mounted on the boundary of the domain [13,14]. The operating principle of the ERT system is typically that of current excitation and voltage measurement. The current is applied into the measurement section through a pair of electrodes which then excites the sensing field. When the conductivity distribution varies, the sensing field varies, resulting in a change in the distribution of electric potential. Likewise, the boundary voltage of the sensing field also changes accordingly. The measured voltage contains information on the conductivity in the sensing field, and the internal flow status can be obtained from further information processing [12]. This is shown in Figure 1. In the case of conducting pipes or vessels, the electrodes need to be insulated from the conducting wall [15].

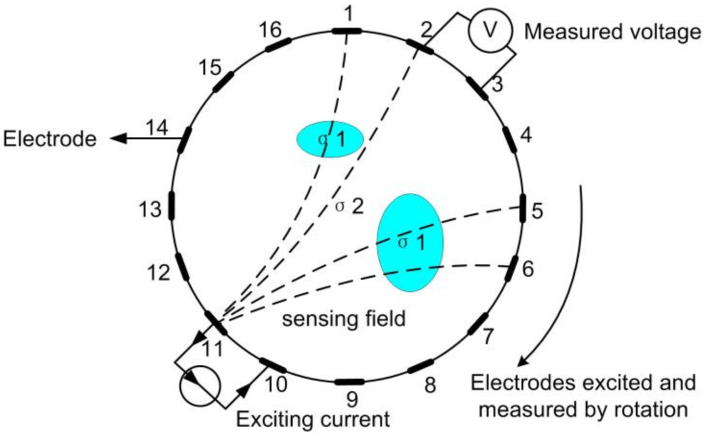


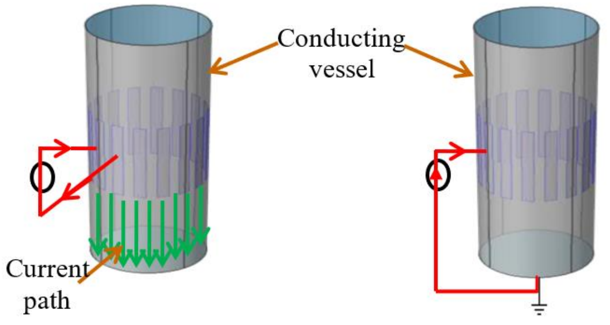
Figure 1. Operating principle of ERT [12]

2.1 ERT Measurement Strategy for Conducting Vessels

A measurement strategy is necessary, especially in ERT, to define an experiment that involves a metal or conducting vessel. In ERT, quantitative data which describe the state of the conductivity distribution inside the vessel are obtained. Good data collection strategies are vital because largely misleading images can be rebuilt if a full set of independent measurements are not collected [16,17]. For all intents and purposes, selecting a strategy that has a good ability to distinguish and high sensitivity to conductivity changes in the process is necessary. There are four main strategies in ERT: the adjacent strategy, conducting boundary strategy, opposite strategy, and diagonal strategy.

The first application of ERT only considered electrode arrangements operating within vessels that have insulating walls and applied the adjacent measurement strategy, which is the most common. This strategy was illustrated previously in Figure 1. It involves injecting current between an adjacent pair of electrodes and measuring voltage from successive pairs of neighbouring electrodes. The injection pair is switched through the next electrode pair until all independent combinations of measurements have been completed. However, most of the process vessels in industry have conducting walls and therefore provide an additional current sink during the measurement process. This causes both reduced sensitivity in the bulk of the material and increased difficulty in obtaining stable measurements referenced to the injected currents [4].

Before applying ERT to an electrically-conducting vessel, an electrical path passing through the vessel wall must be considered. The adjacent strategy is unsuitable for application to the conducting vessel because much of the electrical current from the injection electrode would travel to ground through the material of the wall, rather than through the multiphase mixture, greatly reducing sensitivity. This is known as the grounding effect of the vessel. One possible method of accounting for the conducting vessel wall is to use the wall itself as the ground electrode [5]. The conducting boundary strategy, as discussed previously, was proposed and developed by Wang [7] for conducting vessel walls to overcome the grounding effect. The grounding effect for both adjacent and conducting strategies is illustrated in Figure 2.



(a) (b)

Figure 2. Grounding effect: (a) Adjacent strategy, (b) Conducting boundary strategy

The conducting boundary strategy considers each electrode acting sequentially as a current source, whilst the whole of the metallic vessel behaves as a grounded current sink. In this strategy, all voltage measurements are referenced to the same earth potential as the conducting boundary. The injection and measurement pair of 16 electrodes are tabulated in Table 1. The symbol “e” in the table refers to the electrode. The table shows that, when the electrode acts as a current source, the output potential will be measured on other receiving electrodes. For example, when e1 acts as a source, the output will be measured on electrode 2,3,… until electrode 16. When e2 acts as the source, the output is measured on e1, e3, e4,… until electrode 16. The processes are repeated until all measurements of electrode pairs are attained. The “x” symbol in the table denotes that there is no measurement taken for that particular electrode pair. There are fifteen output measurements for each injected electrode. Because a total of sixteen electrodes are implemented in the research, the total number of measurements is 240, as shown in the following table.

Table 1. Measurement Strategy for Conducting Boundary

Receiver Source	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	No. of measurement
e_1		▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	15
e_2	▨		▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	15
e_3	▨	▨		▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	15
e_4	▨	▨	▨		▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	15
e_5	▨	▨	▨	▨		▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	15
e_6	▨	▨	▨	▨	▨		▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	15
e_7	▨	▨	▨	▨	▨	▨		▨	▨	▨	▨	▨	▨	▨	▨	▨	15
e_8	▨	▨	▨	▨	▨	▨	▨		▨	▨	▨	▨	▨	▨	▨	▨	15
e_9	▨	▨	▨	▨	▨	▨	▨	▨		▨	▨	▨	▨	▨	▨	▨	15
e_{10}	▨	▨	▨	▨	▨	▨	▨	▨	▨		▨	▨	▨	▨	▨	▨	15
e_{11}	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		▨	▨	▨	▨	▨	15
e_{12}	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		▨	▨	▨	▨	15
e_{13}	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		▨	▨	▨	15
e_{14}	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		▨	▨	15
e_{15}	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		▨	15
e_{16}	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		15
Total Measurements																	240

The number of unique measurements, N, in the conducting boundary or 'metal wall' strategy can be defined as shown in Equation (1):

$$N = \frac{n(n-1)}{2} \quad (1)$$

where n is the total number of electrodes [4]. For instance, a total of 16 electrodes used will provide 120 unique measurements. The formula is divided by two because a measurement and its reciprocal contain the same information and are thus counted as one by the formula.

3. Methodology

Prior to building a model using COMSOL Multiphysics, users need to specify the desired space dimension and select the physics interfaces and study type. After selecting the space dimension, Electric Currents of the physics interface under the AC/DC branch and stationary study were selected, respectively, for the simulation study. The following steps were then taken:

i. Creating a physical model using available geometries:
A physical model was developed that mimics a real system. Sixteen electrodes insulated from the column wall were placed equidistantly inside the column.

ii. Defining materials for each domain in the created model:
The materials for each related domain in the model were defined so that it resembles reality. The column itself was defined as stainless steel and the main medium inside the column was water with a conductivity of 8.3 mS/m. For the electrode sensor, a flexible printed circuit board (PCB) with FR4 as the insulating layer was chosen.

iii. Assigning the relevant physics interface and defining the boundary and initial conditions that describe the real experimental setup:
The Electric Currents interface was chosen as this would produce an electrical field and has the electrical potential distribution required for the analysis. It also contains the equations, boundary conditions, and current sources for modelling electric currents in conductive media, thus solving the electric potential. To overcome the grounding effect of the vessel, a conducting boundary strategy was implemented on the model. This meant that each electrode would act sequentially as a current source, whilst the whole of the conducting vessel behaved as a grounded current sink. In this strategy, all the voltage measurements were referenced to the same earth potential of the conducting boundary [18]. A constant current of 5 mA was applied at e1 that acts as the source electrode, and the output voltages from 15 pairs of electrodes from e2 to e16 were measured. At the same time, the column itself was grounded and acted as the current sink. A cross-sectional and 3D view of the ERT model in COMSOL are shown in Figure 3.

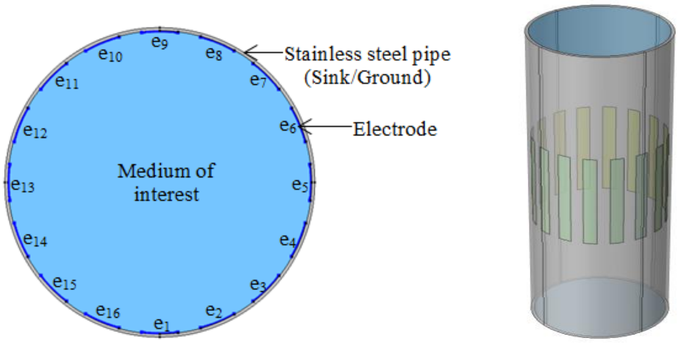


Figure 3. Cross sectional view and 3D ERT model developed in COMSOL

iv. Meshing the model
In a simulation process, meshing geometry can be crucial in obtaining the best results more quickly. Extra fine meshing under a controlled meshing physics setting was chosen, as denser meshing provides a more reliable finite element method (FEM) simulation. Figure 4 displays the meshed system selected.

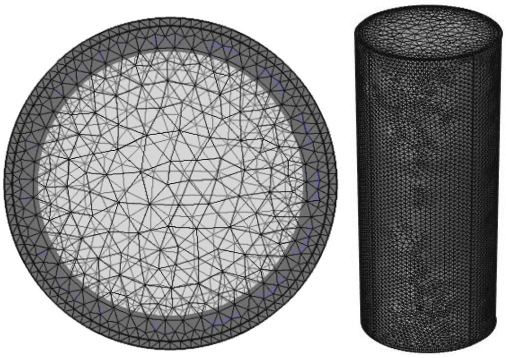


Figure 4. Extra fine meshing using COMSOL Multiphysics

v. Running the study:
The investigated model was simulated using the default solver under stationary study. In applying the stationary solver, it was assumed that the load and deformation do not vary over time. All modelling formulations were based on Maxwell’s equation. The physic interface chosen earlier solves the current conservation equation for the electric potential.

vi. Pre-processing the data for analysis:
Finally, the results were pre-processed and analysed.

4. Results

The COMSOL simulation results for the ERT model using a stainless-steel pipe are presented in this section. The electric potential and streamline current density for the adjacent and conducting strategy on a conducting wall pipe are as shown in Figure 5 and Figure 6 respectively. These supports the theory mentioned earlier where the pipe wall itself need to be grounded when using metal wall. The electric current from the injection electrode travels to ground through the wall material rather than through the multiphase mixture using an adjacent strategy. The adjacent strategy on a metal pipe will cause the equipotential lines around the centred object radiate from the centre of the pipe. Thus, when applying ERT on a metallic bubble column, conducting boundary approach needs to be implemented as the current will travel through the region of interest.

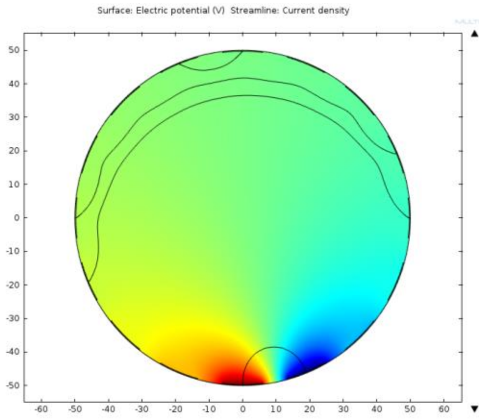


Figure 5. Metal Wall and Adjacent Strategy

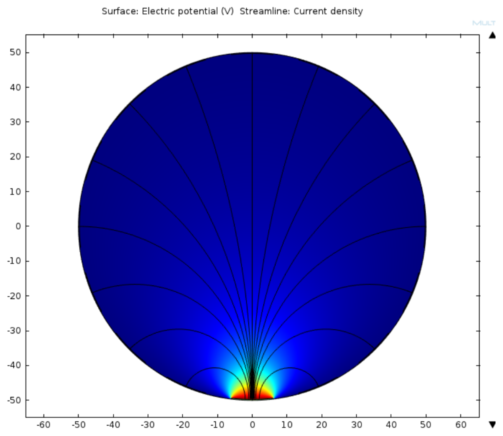


Figure 6. Metal Wall and Conducting Strategy

The effect of potential distribution and current streamline using a conducting boundary strategy for sixteen sensor electrodes were then observed. These are shown in Figure 7. This shows that the current density streamline is scattered evenly towards the ground. This is consistent with the soft field tomography. The electric path is non-linear as it is spread over the entire volume of the system instead of providing a smooth straight line for the current streamline. Regarding potential distribution, this shows that the potential is highly dense at the injection electrode and starts to deteriorate as it travels farther from the source. Thus, the neighbouring electrode will have higher electric potential and the value will decrease accordingly for the receiving electrode.

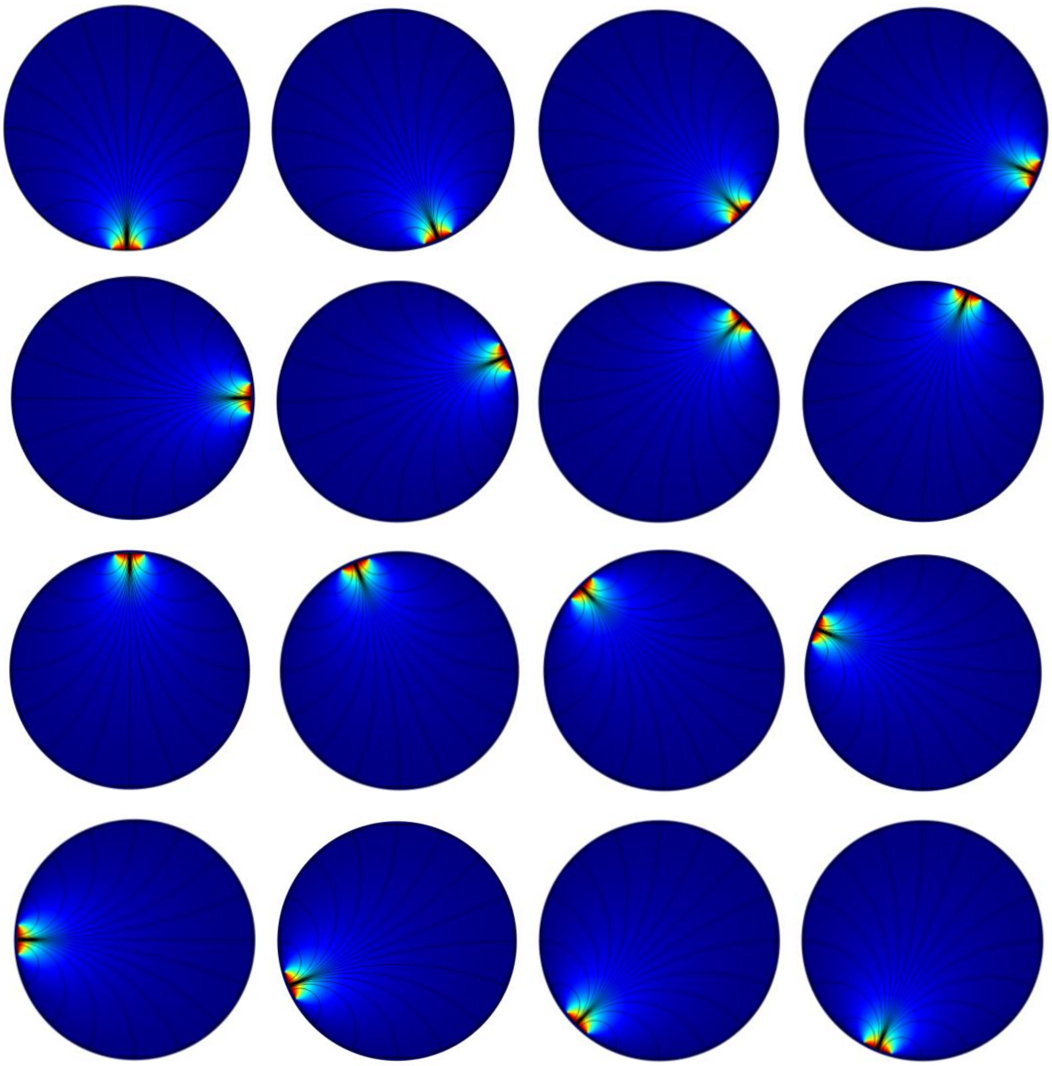
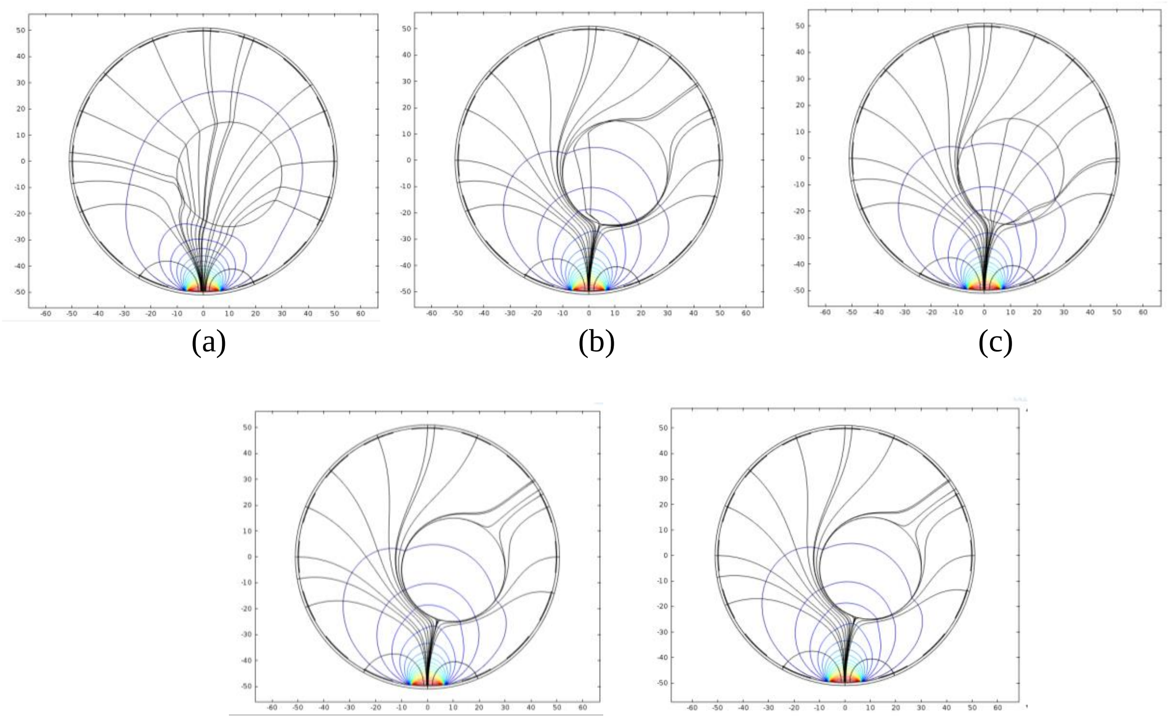


Figure 7. Electric potential and streamline current density for each electrode excitation

A 20 mm radius of an annular phantom was then employed and placed at centre coordinates of (10, -5). When a 5 mA current was injected at the first electrode, e1, the effect on the different conductivity distribution towards the electric field contour and the current density streamline was observed. The outputs are displayed in Figure 8. These show that the sensing field is strongly affected by the conductivity distribution within its sensing region. The field will be deflected based on the material distribution. Similarly, the electrical potential contour distribution and the boundary voltage of the system will vary accordingly.



(a) (b) (c)

(d) (e)

Figure 8. Effect of different conductivities, σ on the contour of electric potential with current density streamlines

(a) $\sigma = 3.477 \times 10^{7}$ S/m, (b) $\sigma = 1 \times 10^{-4}$ S/m, (c) $\sigma = 1 \times 10^{-3}$ S/m, (d) $\sigma = 1 \times 10^{-14}$ S/m, (e) $\sigma = 5 \times 10^{-15}$ S/m

5. Conclusion

The forward problem of the system has been designed and modelled in the finite element software; COMSOL Multiphysics. The conducting boundary approach was applied in the measurement part of the research so that the current will travel through the region of interest instead to the wall pipe. the current density streamline is scattered evenly towards the ground. The potential distribution is highly dense at the injection electrode and starts to deteriorate as it travels farther from the source. Thus, the neighbouring electrode will have higher electric potential and the value will decrease accordingly for the receiving electrode. From the research, it is proof that the sensing field is strongly affected by the conductivity distribution within its sensing region. The field will be deflected based on the material distribution. Similarly, the electrical potential contour distribution and the boundary voltage of the system will vary accordingly.

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