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Simulation and performance characteristics of rock with borehole using Visual Finite Element Analysis

Mohammed Mnzool [1], Ahmed Al-Mukhtar [2,3], Amani J. Majeed [4*], Ahmed Arafat [1,5], Ehab Gomaa [1,5]

[1] *Taif University, Taif, Saudi Arabia*
[2] *Bauhaus-Universität Weimar, Weimar, Germany*
[3] *Al-Hussain University College, Karbala, Iraq*
[4] *University of Basrah, Basrah, Iraq*
[5] *Suez University, Suez, Egypt*

**Corresponding author: e-mail amani.majeed@uobasrah.edu.iq*

Abstract

Purpose. This study aims to investigate fluid flow and heat transfer within rocks containing boreholes, focusing on the complex mechanisms within hot reservoirs. Non-commercial finite element (FE) software is used to visualize and present the results.

Methods. The study involved the use of FE method with Visual Finite Element Analysis (VisualFEA) software to analyze the coupled phenomena of fluid flow and heat transfer in a rock sample. Special attention was given to incorporating material structure and geotechnical analysis in the software, as well as the treatment of cracked elements. In addition, the validation was done by comparing the current numerical solution using VisualFEA with the numerical solution using ANSYS Software.

Findings. The study findings highlight the capabilities of VisualFEA software to accurately represent fluid flow, stress, and heat transfer in borehole-containing rocks. The results include insights into flow direction within the borehole, temperature distribution, and the validation of the software performance against expected system behavior. The study demonstrates the effectiveness of VisualFEA in handling complex loading and its ability to visualize multiple flow directions within a 2D model. The results are presented in the form of contours and curves.

Originality. This study contributes to the field demonstrating the application of VisualFEA software in analyzing fluid flow and heat transfer in rocks with boreholes. The focus on incorporating material structure, geotechnical analysis, and treatment of cracked elements adds originality to the study, providing a comprehensive understanding of the coupled phenomena in hot reservoirs.

Practical implications. The practical significance of this study is in the validation and benchmarking of VisualFEA software for studying fluid flow and heat transfer in geotechnical application. The findings can be utilized by geotechnical engineers and researchers to better understand the behavior of borehole-containing rocks under specific pressure and thermal loading conditions. The insights gained from this study can be used in decision-making processes related to resource mining, reservoir engineering, and geothermal energy use.

Keywords: *coupled simulation, fracture, rock mechanics, transient analysis, VisualFEA*

1. Introduction

Deep beneath the surface, in the heart of the Earth, there is a hidden world of intense heat and pressure. Geothermal regions are places of constant movement and change, where molten rock and superheated water surge and swirl, carving out channels and pathways that stretch for miles. The hydrodynamic behavior of a fractured reservoir needs to be studied in detail. Therefore, the distribution of pressure and flow in the cracked rock has been presented and simulated using different models and codes. The fracture and fluid models have been presented separately [1]-[6]. However, the thermocouple study was obscure. On the other hand, the modeling of complex coupled transient and dynamic processes in geosystems is being extended to provide more precise and realistic evaluation.

Until now, only a few publications have dealt with the coupling of thermal, fluid, and structural analyses of the rock. However, most of the work is based on commercial software and codes. These are either difficult to use or expensive, and the relevant codes are either not applicable or incomplete.

Stresses, strains, and temperatures are examples of scalar data obtained from FEA. Contouring is the most widely used method for visualizing scalar data. Therefore, VisualFEA [7] provides easier steps for initiating the geometry and different options for the meshing process. The main objective of VisualFEA is to overcome such barriers between the user and the software [7]. VisualFEA/CBT, which is used in this work, is

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an exceptionally easy-to-use FEA software program with powerful pre- and post-processing capabilities and a number of options for analysis. This CBT (computer based training) version of the software can be used as an excellent educational tool due to its unique feature of simulating FEA procedures ranging from element modeling to stress computations [7].

VisualFEA multiphysics program is recommended for thermal behavior, the combination of solid and fluid mechanics in a solid body. Due to the complexities of simulating fluid flow, structure, and thermal problems, several steps and iterations are required. Therefore, critical procedures are required (Fig. 1a). Nevertheless, the analysis step also contains some intermediate requirements (Fig. 1b).

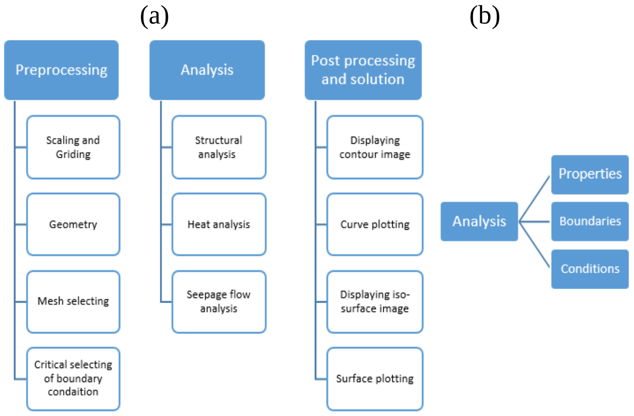


Figure 1. Schematic representation of the analysis procedures: (a) simulation sequence; (b) analysis sequences

VisualFEA [7] has three categories of analysis subjects: structural analysis, heat conduction analysis, and seepage analysis (Fig. 1). Structural analysis can be coupled with either heat analysis or seepage analysis. In coupled analysis, it is necessary to assign two different types of properties to one model. Moreover, in a coupled analysis of structure and heat conduction, we specify the heat boundaries by selecting a surface temperature, convection, heat flux, and so on. Additionally, the structure analysis treats these conditions as thermal loadings. However, we select the heat property for the entire volume using variables such as volume heat, line heat, and insulation.

This work focuses on the modelling of fluid and thermal applications, where the capability to simulate the system infiltration and heat flow is needed. The results are visualized with vectors, arrows, and colors. We present the temperature distribution, stresses, and flow direction. Mostly, they agree with the experimental behavior, as well as with previous simulation works [8]-[12].

Previous work has studied and described the behavior of notch cracks under the influence of bore pressure using Franc2D [8]. However, Franc2D [13] has no fluid parameters; the crack propagation behavior was consistent with experimental results [14], [15]. This is an FE simulator for solid rock fracturing. The cracking behavior under structural boundary conditions is simulated in different works using Franc2D [9], [13]-[15].

So far, the world has developed and distributed numerous commercial or academic programs for FEA [16]. However, most of them are not very accessible for many potential users of the method, due to various reasons: complexity of usage, high expenses, restricted portability, functional limitations, and so on.

Until now, there have been only a few publications on the coupling of thermal fractures, fluids, and structural analysis. However, most of the work was based on unrealistic assumptions, such as constant propagation velocity of secondary thermal fractures, closed secondary thermal fractures, no interaction of secondary thermal fractures, etc. [9]-[12]. The main geothermal energy source is dry, non-permeable rock.

This study proposes the use of FEM to simulate thermal stresses, creating a fracture surface, fluid flow with a hot reservoir, and crack growth propagation. This is an inverse study to estimate the fracture according to fluid flow and thermal analysis. It is proposed to use VisualFEA to simulate thermal stresses, creating a fracture surface, fluid flow in a hot reservoir, and crack growth propagation.

2. Models and boundary conditions

Researchers study geothermal circulation system productivity at higher flow rates through seepage analysis. Therefore, we need to consider the flow rate and velocity potential maps carefully. We investigate the stress analyses structurally as indicators of load distribution and cracking.

We assign the flow boundaries, which represent the confined and open heads, pore pressure, point source, and flux.

Modeling of complex coupled transient and dynamic processes in geosystems has increased the need for more precise validation and evaluation. We visualize the results using vector data and arrows. This study presents an example of coupling between fluid flow, thermal load, and solid deformation.

Due to the difficulty in assessing real conditions a few thousand meters underground, the boundary conditions are assigned virtually. We must assign specific boundary conditions and make certain assumptions. The isotropic analysis is assumed to be constant, that is, the heat flow and density are constant. In this work, structural, thermal, and gradient analyses were conducted. We coupled 3D solid structural analysis with volume heat. We selected the transient analysis to simulate flow in a porous medium. Figure 2 shows the rock block quarter obtained with VisualFEA through symmetric geometry.

For realistic results, we recommend using fine meshes. However, the user experience and iteration process influence the choice of meshes and their distribution. In structural problems, the fine meshes are needed only in the location expected to have a higher stress to avoid the time-consuming and difficult running (Fig. 2). The mesh-dividing ratio decreases towards the curve.

The distribution of heat along the hole is proposed. In this case, at least one surface on the injection side should be considered. We need to determine the other two sides, which are in the direction of heat or fluid flow. The heat flow per unit area (heat flux, q) has been assigned to the bore surface and to the boundary. The heat flux per unit area (heat flux) has been assigned equal to 10 W/m^2 to the bore curve and 5 W/m^2 to the boundary. The hole curve has a temperature of 150°C. The opposite two surfaces have a convection property with an ambient temperature of T_∞ and a unity convection constant h. The bore and the boundaries also define the confined head. In the meantime, a uniformly distributed load is applied to the borehole. The structural boundary conditions for the two surfaces beside the hole are fixed in the x and y directions. The loading conditions can be combined into one case (Fig. 3). Additionally, the thermal and flow conductivity coefficients can be assigned for isotropic or orthotropic systems.

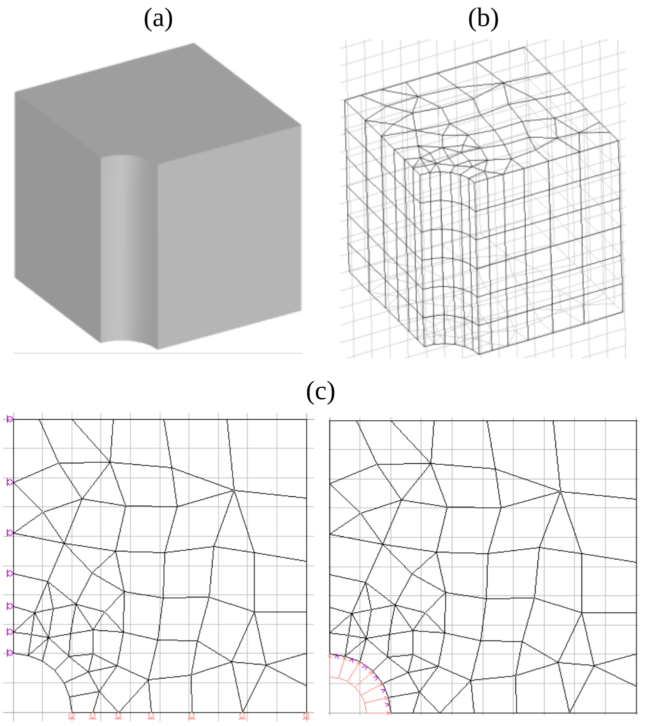


Figure 2. FE models, meshes and boundary conditions: (a) quarter geometry; (b) meshes and elements; (c) the boundary conditions, and load conditions

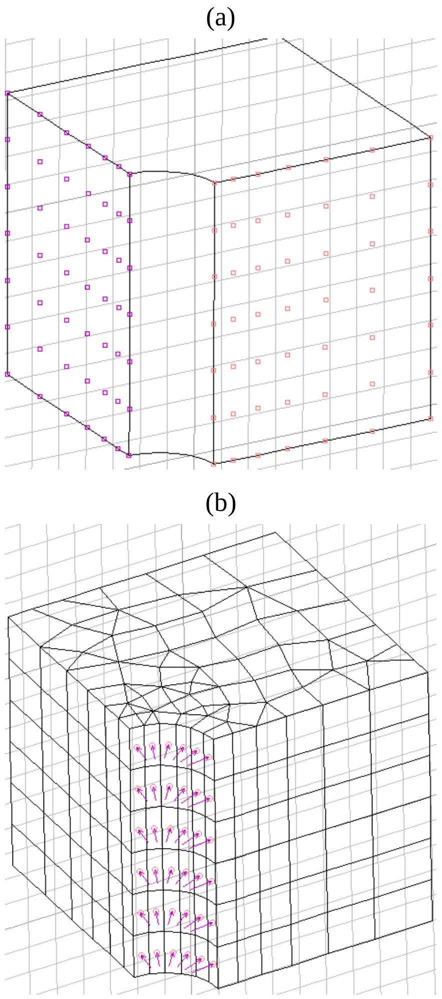


Figure 3. Fixities and loading direction: (a) structural boundary; (b) loading conditions along the hole

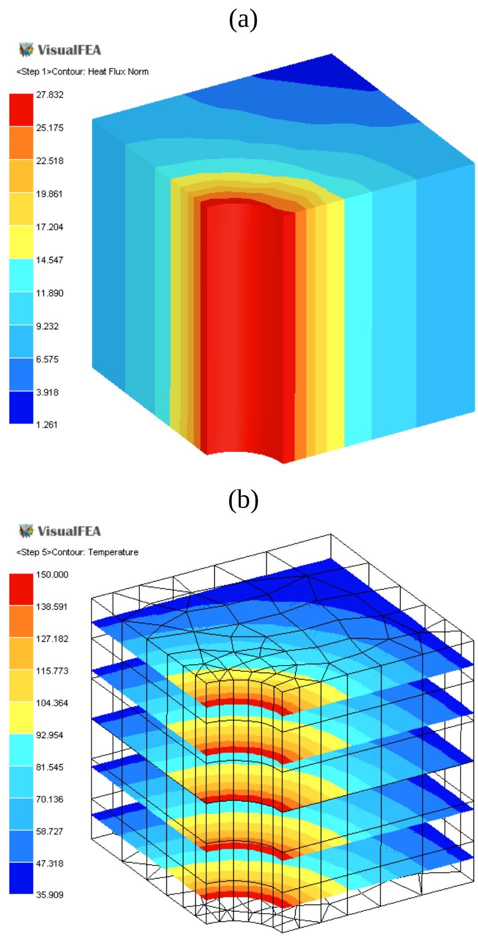
The structural material properties are determined by Young's modulus of elasticity and Poisson's ratio. The isotropic solids with E = 9032e03 Pa and a passion ratio of 0.22 are used. Traditionally, elements are assigned material properties. Nevertheless, the specified element can have certain properties and conditions.

Therefore, thermal, linear, bilinear, and hydrostatic loads can be combined in a single model as needed. After solving the problem of thermal effects, the analysis can be switched to structural analysis to leverage the advantages of solid mechanics properties and conditions. In this work, a thermal load and uniformly distributed normal load acting on the bore surface were selected (Fig. 3b). Different visualizations are supported within FE analysis.

3. Results and discussion

3.1. Simulation of structural and heat analysis

We assign the temperature to the selected meshed surfaces. The bore wall is simulated at 150°C, while the other orthogonal walls – under convection condition. The ambient temperature is also possible to determine. The hydraulic conductivity function is defined. Therefore, the conductivity factor and pore pressure are defined. The heat boundaries are temperature, heat flux, convection boundary conditions, and heat source [17]. Three-dimensional solid geometry, structure, volume transient heat, and linear elastic are selected. The body is considered a volume of heat. The conductivity function K is equal to 1 (isotropic), that is, it is constant in different directions. The temperature distribution and heat flux are shown in Figure 4.



(c)

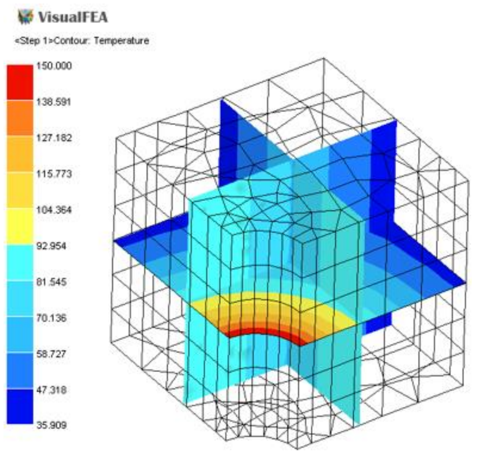


Figure 4. Different results visualization, heat flux to the surface, temperature distribution, and iso-surface of parallel planes, T = 150°C

Since there is no precisely similar case in the literature, validation is done by comparing the current numerical solution using VisualFEA with the numerical solution using ANSYS Software. The ANSYS R18.1 software analyzes the model (Fig. 5). The results show that the distribution achieves an error percentage of 0.01 for temperature and 0.2 for heat flux. Hence, the current FE model using noncommercial VisualFEA has been benchmarked.

3.2. Simulation of structural and heat analysis

It should be emphasized that the geomechanics and stress patterns can also be simulated using VisualFEA. The Mohr circle also presents the principal and maximum shear stresses. Under the shearing fracturing mode, the maximum shear and equivalent stress can control the site of cracking (Fig. 6a-c). On the other hand, the normal stresses in the *x*- and *y*-directions refer to the possibility of flowing in these directions under the opening fracturing mode Figure 6d.

VisualFEA facilitates volume visualization through iso-surface rendering, as illustrated in Figure 7a, b, it shows the flow direction for structure and heat conditions. The head distribution and velocity vectors for this state were obtained through flow and heat simulation. The arrows show the direction of flow along the fractured surface that agrees with the structural analysis (Fig. 6). The 2D model agrees with 3D flow and displacement (Fig. 8).

The coupled solution between heat and structural boundary conditions can illustrate how temperature influences crack formation through shear stress. An increase in temperature difference between the hole and the rock leads to an increase in the shear stress, causing the crack to open, as shown in Figure 9.

The stress is the key to rock mechanics applications. Therefore, in the case of hot, dry rock, cryogenic treatment is used to enhance the cracking network [9], [18].

It is concluded that an increase in the borehole temperature leads to an increase in the developed stress in fractured rock.

3.3. Simulation of structural and water flow

Reference [10] describes the study of thermal fractures. However, they did not simulate the fluid flow or heat exchange between the cold flow and the hot reservoir.

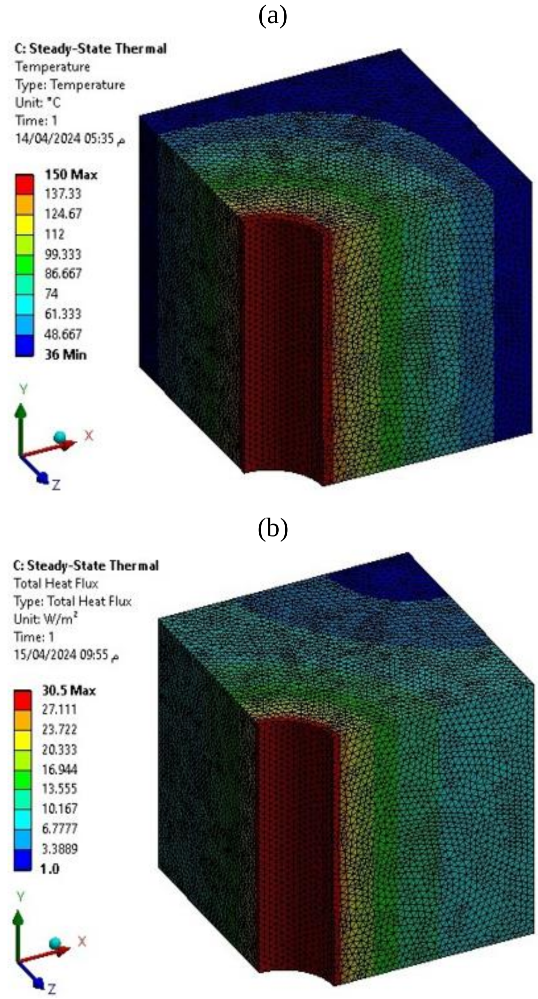


Figure 5. ANSYS model: (a) the temperature distribution; (b) the heat flux

The seepage analysis serves as the basis for determining the property and boundary of the water flow direction. As shown in Figure 10, the rendering results display the hydraulic head measurement. In this part of the simulation, the confined head is selected. A flow path and normal velocity represent the water flow route (Fig. 10).

Figure 10 illustrates the fluid flow direction (velocity field) using lines and solid arrows on the surface. We use vector arrow directions to improve visual comprehension of the computed results, which are based on the defined conductivity and pore pressure (Fig. 11). The flow direction is simulated. 2D model agrees with 3D (Fig. 12).

3.4. Coupling of thermal and structural analysis

The interface surface is also possible to incorporate into the structural properties. We can assign isotropic and orthotropic properties, just like we do with thermal and fluid properties. The structural boundary conditions are assigned using fixity in the *x* and *y* directions.

However, it is possible to combine the loading conditions. Therefore, we can combine thermal load, linear load, bilinear load, and hydrostatic load. The coupling is based on a structural analysis. A flow path represents the water flow route.

The fluid flow direction is indicated by line arrows and solid arrows on the surface (Fig. 13). Moreover, Figure 14 shows the temperature distribution throughout the module.

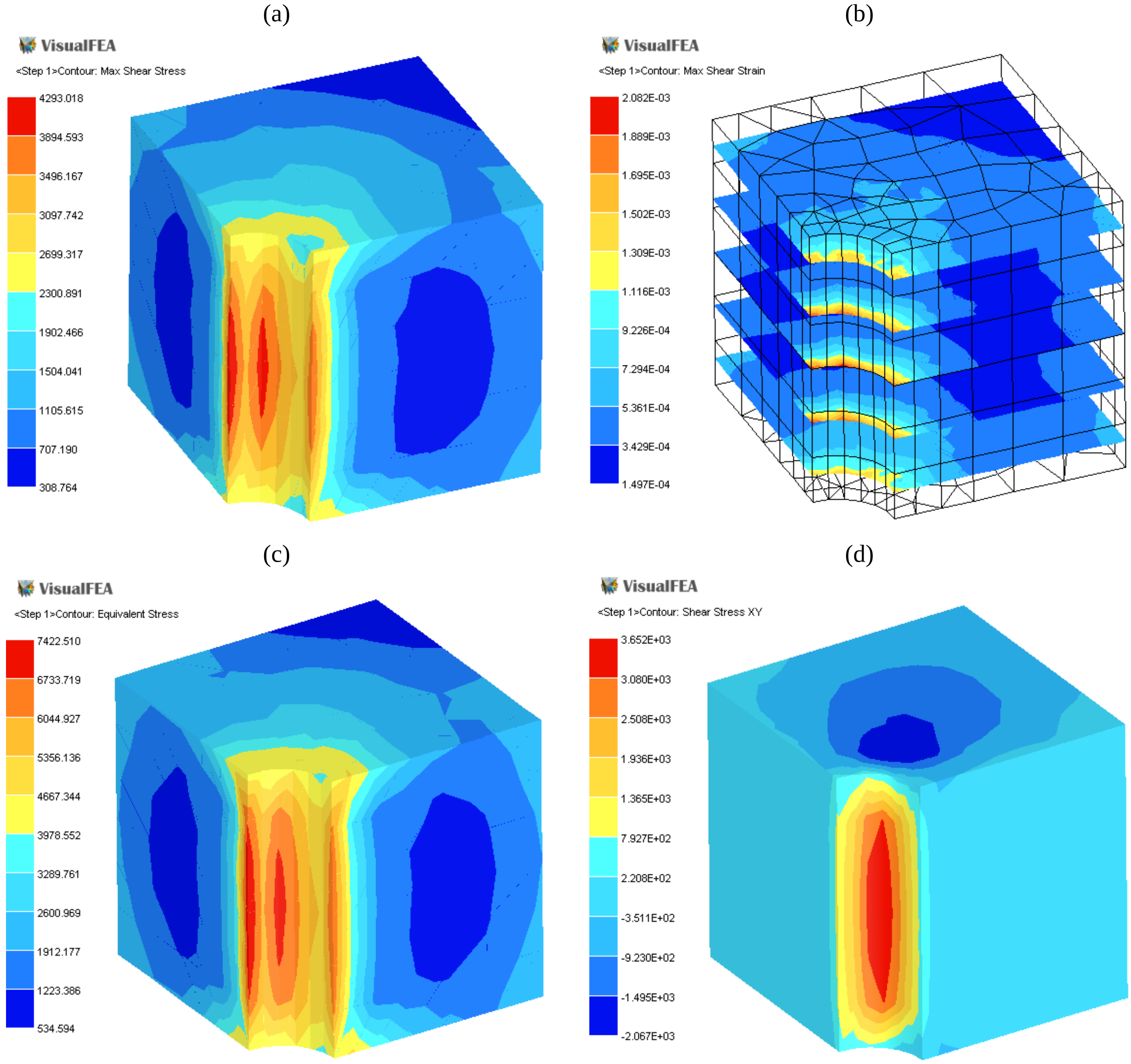


Figure 6. Fracture densities according to maximum shear stress and estimation of crack location, T = 150°C: (a) maximal shear stress; (b) maximal shear strain; (c) equivalent stress; (d) shear stress in x-y plane

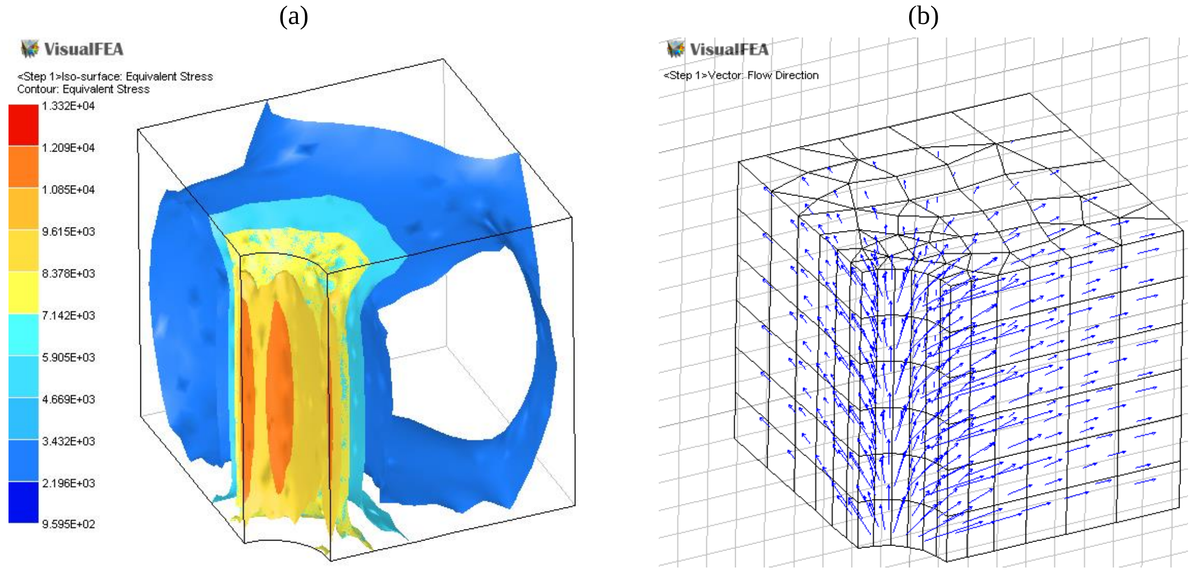


Figure 7. The relationship between the developed stress and the flow direction: (a) iso-surface rendering of stresses; (b) flow direction represented by arrows

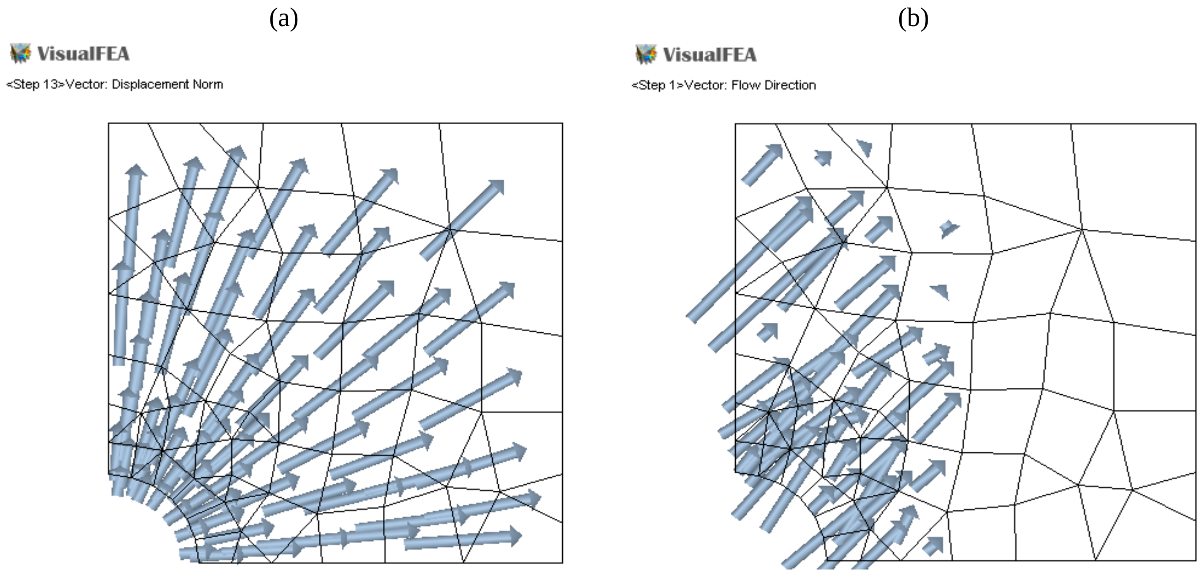


Figure 8. 2D-coupled heat and structure model of the flow direction: (a) normal displacement; (b) flow direction

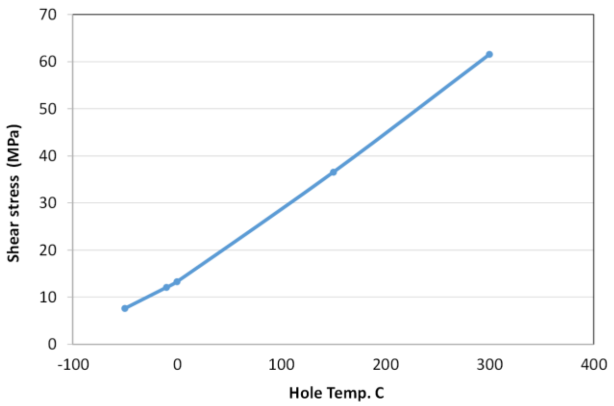


Figure 9. The effect of temperature to produce aperture opening stress (shear stress in rock), T ambient = 35°C

The maximum temperature at the hole is simulated. The borehole surface is heated according to boundary condition, $T = 150$°C. Hence, the temperature decreases along the rock block length.

4. Conclusions

VisualFEA is integrated software for FEA, which is an advanced numerical technique to solve and analyze physical problems arising in many fields of science and engineering. VisualFEA incorporates all necessary functions for multiphysics simulations into a single executable code. This software allows a high degree of thermal simulation and seepage analysis. But unfortunately, the evaluation of the current system shows that it has no capability of modeling multi-physics problems involving fluid, heat, and stress at the same time. Nevertheless, multiple loading types are possible to combine.

However, there are special treatments for crack tips; no real fracturing analysis exists within VisualFEA. VisualFEA only uses the crack tip element to model the stress distribution at the crack tip. But it is unable to determine the crack initiation or propagation. Future work should investigate this software ability to create an open crack wall and prevent thermally hydraulic fracture closure. The VisualFEA software allows for the investigation of various parameters. You can investigate the effects of heat parameters, structural parameters, and seepage conditions. You can use this code to solve a wide range of problems, such as elasticity and heat transfer problems. We incorporate different analysis methods to visualize the results.

In shearing fracturing mode, the maximum shear and equivalent stress can control the cracking site. The process could incorporate both cracking and hydraulic fracturing. The coupling between structural and thermal analysis has been conducted. We have coupled the plane strain structural analysis with 2D plane heat. The transient analysis has been selected to simulate flow in a porous medium. We introduced a block of rock containing a borehole.

We propose the distribution of heat around the hole during the loading and pumping process. VisualFEA provides easier steps for initiating the geometry in 2D and 3D, with different options for the meshing process. The thermal conductivity coefficient in isotopic or orthotropic conditions can be assigned. VisualFEA has three categories of analysis subjects: structural analysis, heat conduction analysis, and seepage analysis. You can combine structural analysis with either heat analysis or seepage analysis. It is necessary to assign two different types of properties to one model. The nodal values computed from the heat conduction analysis, not the thermal load, specify the temperature distribution in a coupled analysis of structure and heat conduction. The simulation of fluid flow needs several steps to determine the boundary conditions, constrain the body, and specify the pressure inside the crack. The structural material properties are determined by Young's modulus of elasticity and Poisson's ratio. Higher flow rates increase the performance of a geothermal system if the reservoir temperature is known.

Author contributions

Conceptualization: AAM, AJM; Data curation: MM, AA, EG; Formal analysis: AAM, AJM; Methodology: AAM, AJM; Resources: MM, AA, EG; Software: AAM, AJM; Validation: AAM, AJM; Visualization: MM, AA; Writing – original draft: AAM, AJM; Writing – review & editing: MM, AA, EG. All authors have read and agreed to the published version of the manuscript.

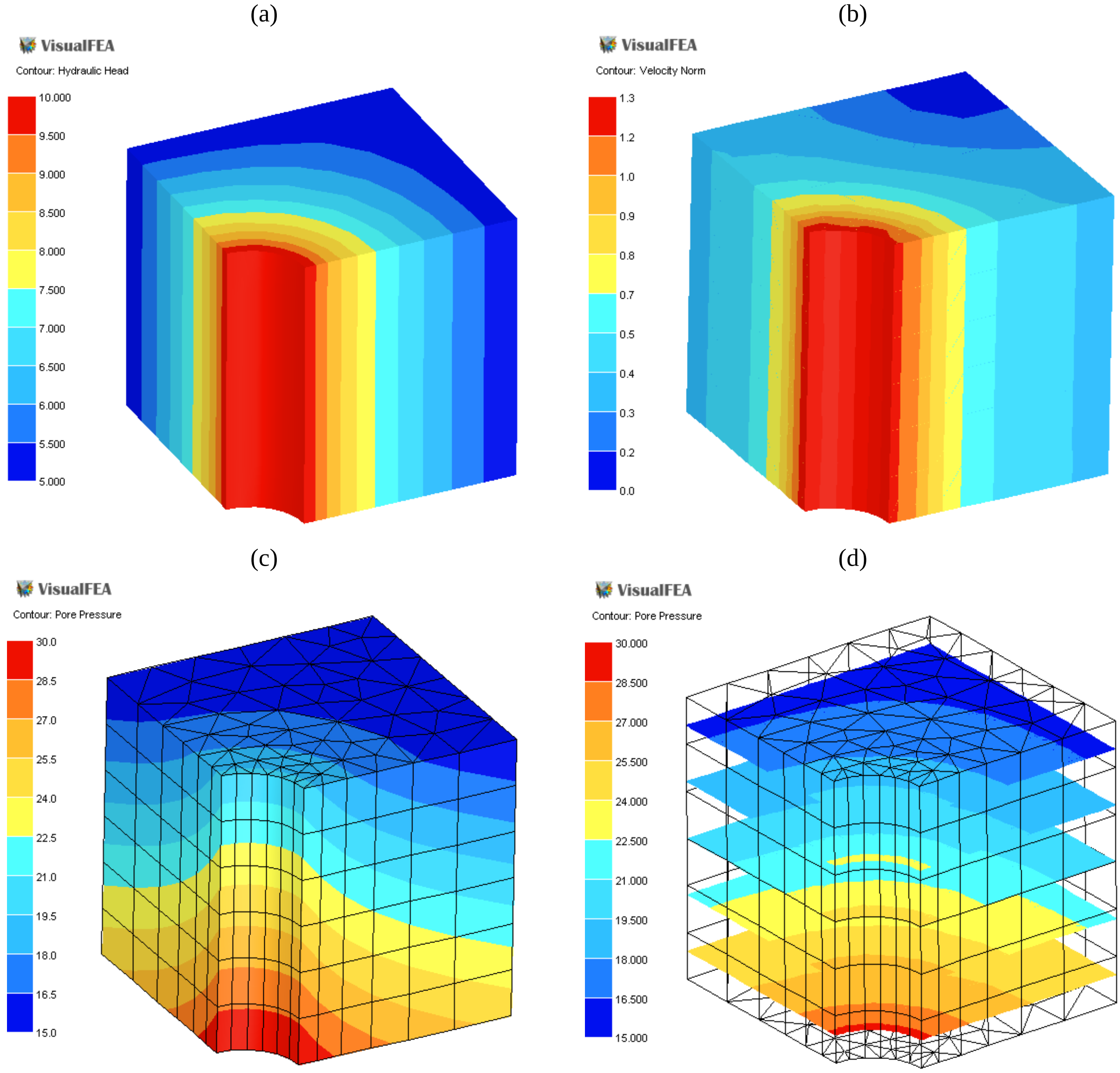


Figure 10. Hydraulic flow, velocity and pore pressure distributions: (a) hydraulic head; (b) velocity vector; (c) pore pressure; (d) pore pressure in the form of layers

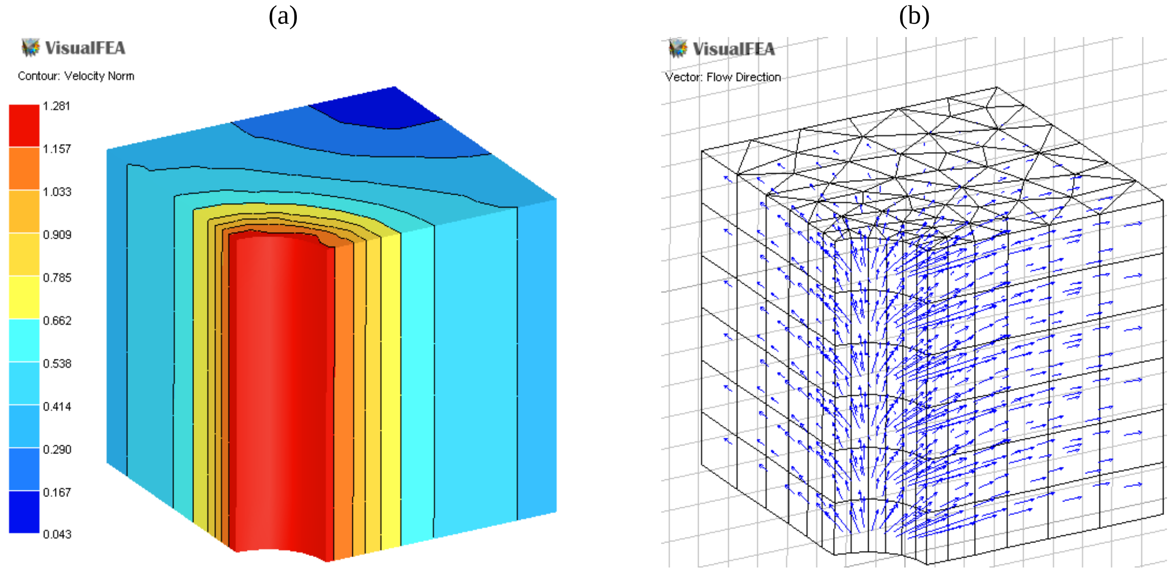


Figure 11. Flow distribution and velocity: (a) velocity normal to the bore surface; (b) the arrows show flow velocity and directions

(a) (b)

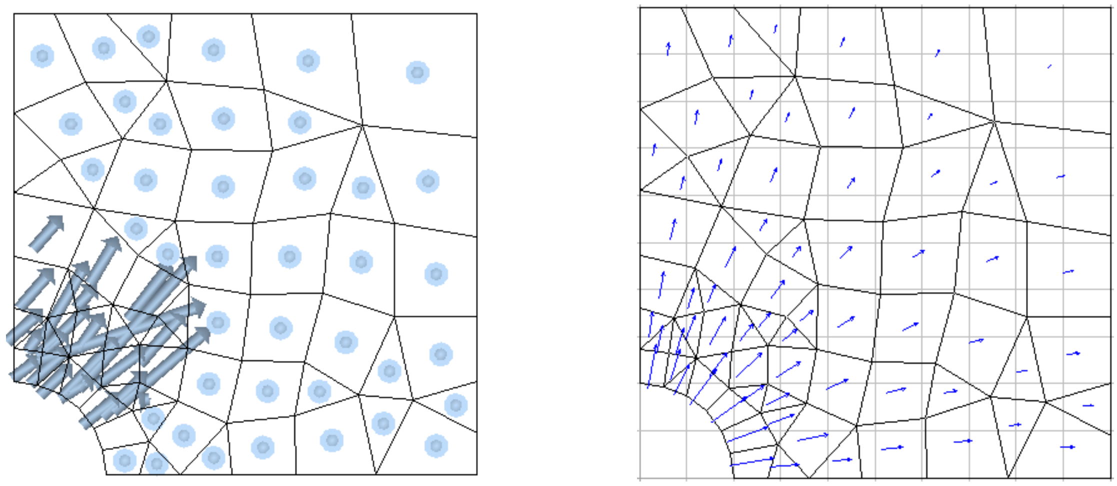


Figure 12. 2D-Flow directions represented by arrows, ground water direction: (a) 3D arrows direction; (b) 2D flow direction

(a) (b)

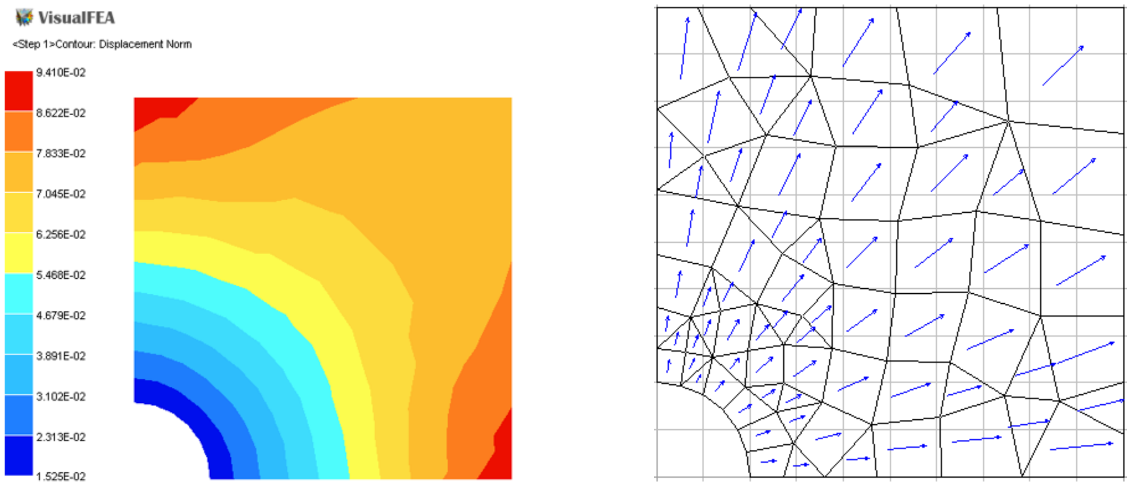


Figure 13. Normal displacement represented by vector: (a) displacement distribution in term of contour; (b) displacement direction in term of arrows

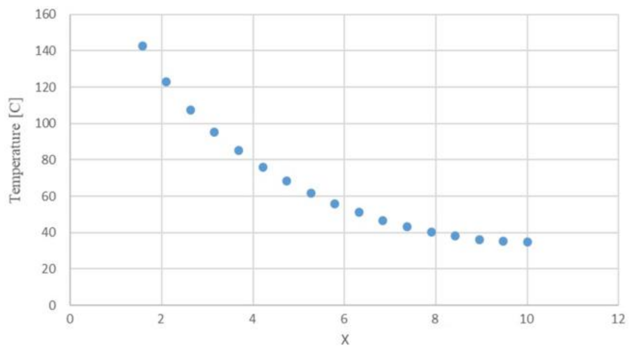


Figure 14. Temperature distribution along X-axis

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Моделювання та експлуатаційні характеристики породи із свердловиною за допомогою візуального аналізу методом скінченних елементів

М. Мнзул, А. Аль-Мухтар, А.Дж. Маджид, А. Арафат, Е. Гомаа

Мета. Вивчення потоку рідини та теплопередачі у породах, що містять свердловини, з акцентом на складні механізми у гарячих резервуарах із застосуванням методу скінченних елементів (МСЕ).

Методика. Дослідження передбачало використання МСЕ з програмним забезпеченням Visual Finite Element Analysis (VisualFEA) для аналізу пов'язаних явищ потоку рідини та теплопередачі в зразку породи. Особлива увага приділялася включенню структури матеріалу та геотехнічного аналізу до програмного забезпечення, а також дослідженню елементів з тріщинами. Крім того, перевірка проводилася шляхом порівняння поточного чисельного рішення із використанням VisualFEA з чисельним рішенням із застосуванням програмного забезпечення ANSYS.

Результати. Доведена можливість програмного забезпечення VisualFEA точно відображати потік рідини, напруження та теплообмін у породах, що містять свердловину. Результати включають інформацію про напрямок потоку всередині свердловини, розподіл температури та перевірку продуктивності програмного забезпечення на предмет відповідності очікуваній поведінці системи. Дослідження демонструє ефективність VisualFEA при обробці складних навантажень та його здатність візуалізувати декілька напрямків потоку у рамках 2D-моделі.

Наукова новизна. Дане дослідження демонструє застосування програмного забезпечення VisualFEA для аналізу потоку рідини та теплопередачі в гірських породах зі свердловинами. Акцент на врахуванні структури матеріалу, геотехнічному аналізі та дослідженні елементів з тріщинами додає оригінальності дослідженню, забезпечуючи всебічне розуміння пов'язаних явищ у гарячих резервуарах.

Практична значимість. Результати можуть бути використані інженерами-геотехніками та дослідниками для кращого розуміння поведінки породи, що містить свердловини, за умов певного тиску і термічного навантаження. Отримані в ході цього дослідження знання можуть бути використані в процесах прийняття рішень, пов'язаних із видобуванням корисних копалин, розробкою родовищ і використанням геотермальної енергії.

Ключові слова: *спільне моделювання, руйнування, механіка гірських порід, аналіз перехідних процесів, VisualFEA*

Publisher's note