IOP Conference Series: Earth and Environmental Science

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To cite this article: Georgia George Mwaipopo and Cheng Yuanfang 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **254** 012015

IOP Conf. Series: Earth and Environmental Science **254** (2019) 012015 doi:10.1088/1755-1315/254/1/012015

Geomechanical modelling of a Geothermal reservoir in Tanzania

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Abstract. Countries that are favored by being situated within the East African Rift System, Tanzania is among them. Geothermal energy is a potential renewable source that should be taken into account in Tanzania's energy mix. Computational Fluid Dynamic (Mathematical modeling and numerical simulation) are taking into account for predicting of geothermal reservoir. Preliminary, geothermal survey studies have been done in Tanzania. However, the available data is inadequate partly because of limitations in traditional measurements and visualization techniques for the geothermal reservoirs located deep underground. This paper presents computational fluid dynamics (CFD) technique which has been employed to address the limitations by giving an insight into these complex flows that are often difficult, expensive or impossible to study using traditional techniques. The discretized Euler-Eulerian equations are solved in Fluent 12 software for the conservation of mass, momentum, energy and species. The predicted results indicate that thermodynamic properties such as the rate of temperature and pressure drop along the fractured porous rock (hole path) in the concerned study area were 0.02^{o}C per meter and 0.025 bar per meter, respectively. Further, the predicted steam quality at outlet is 0.9.

1. Introduction

Geothermal reservoir a subsurface region where the rocks contain hot water and/or steam that can be withdrawn using wells or can flow out to the surface by natural condition through fractured rock (hot spring) and put to practical use for generating electricity or for direct heating. Geothermal energy from these reservoirs is heat energy generated and stored in the Earth (Gudmundur, Karsten, & Marcelo, 1986). High temperature, working fluid and permeable flow channels are the elements of a geothermal reservoir. Therefore, geothermal energy (power) is a reliable, low-cost, environmentally friendly, renewable energy and suitable for generating electricity.

Fluid (gas and liquid) flow are governed by partial differential equations (PDE) which represent conservation laws for the mass, momentum and energy. Computational fluid dynamics (CFD) is the art of replacing such PDE system by a set of algebraic equations which can be solved using digital computers. CFD provides a qualitative (quantitative) prediction of fluid flows by means of; mathematical modeling (PDE), numerical methods (discretization and solution techniques) and software tools. CFD gives an insight flow patterns that are difficult, expensive and/or impossible to study using traditional (experimental) techniques. The objective of this paper is to conduct geomechanical modeling (numerical modeling in 3D) at Songwe-Mbeya site in Tanzania for detailed analysis of the complex flow and thermal fields typical to geothermal reservoir flows.

1.1. *Geologic Setting*

Songwe-Mbeya geothermal site, is located in south region of Tanzania (945,087 km^2) in East Africa, as shown in Figure 1. Tanzania is among the countries that are favored by being situated within the East African Rift Valley system [3]. The estimated geothermal energy potential as per previous studies exceeds 650MW as reported by McNitt [4]. The country's total grid installation capacity is 1,522.3 MWe; Hydro 37%, gas 33% and fossil fuels 30%, nowadays national power system relying on hydropower and gas power. The conditions for high-enthalpy resources are principally favorable in Mbeya region due to the presence of active faults, allowing fluid flow, a young volcanic heat source which is sparse in other parts of the western branch of East African Rift System and surface manifestations of hot springs indicating geothermal activity in the subsurface, [5].

Geothermal survey started its works of investigating on 1982, the available data was inadequate partly because of limitations in traditional measurements and visualization techniques for the geothermal reservoirs located deep underground. CFD techniques have been employed to address the limitations by giving an insight into these complex flows that are often difficult, expensive or impossible to study using traditional techniques.

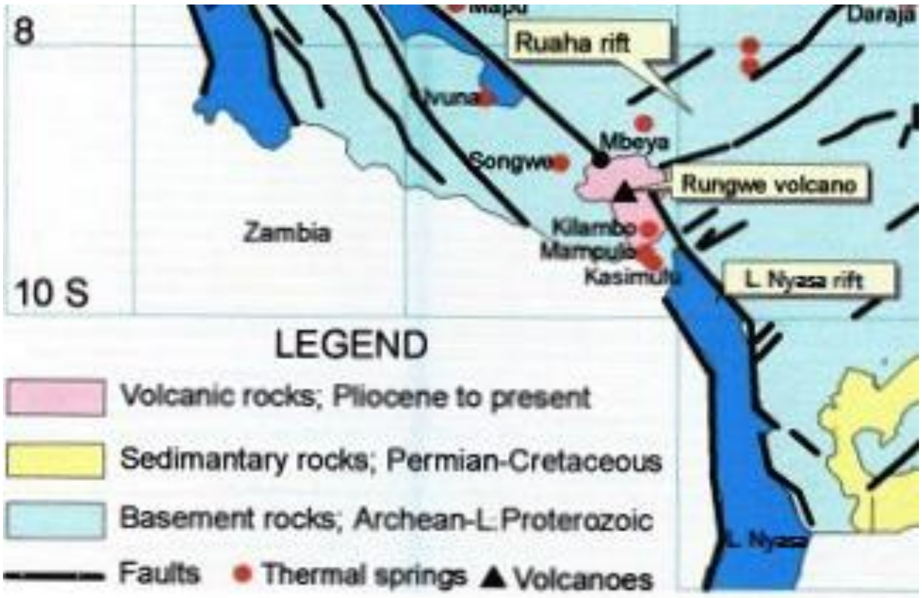

Figure 1. Simplified geologic map of study area, Mbeya- Songwe [3].

Mathematical models for geothermal systems usually describe the three-dimensional flow of hot water, steam and transport of heat in porous media. The basic governing equations may be Songwe valley area, which is situated about 27 km west of Mbeya town and located between Latitude 8^{o}50' S-8^{o}56'S and Longitude 33^{o}10' E-33^{o}15'E. The springs have maximum measured earth surface temperature of 86^{o}C, reservoir subsurface temperatures are between 220^{o}C - 276^{o}C, total discharge 50-75L/s. The estimated reservoir depth at Songwe site is between 1.5km - 3 km with total usable power potential of is 107 MW [3].

Expressed in terms of pairs of basic unknown thermodynamic quantities, for example, fluid enthalpy and pressure, fluid density and internal energy, pressure and temperature or pressure and saturation temperature. The geomechanical modeling of a geothermal reservoir is composed mainly to the reservoir model, the model is based on the mathematical description of fluid flow through porous media. Final the reservoir simulation is developed in this study for the describing and predicting the temperature and pressure distribution in the fractured rock (hole) of a Songwe geothermal reservoir. The modeling approach is based on the CFD technique by solving the transport equations for multiphase flow in porous media (fractured rock).

2. Methods

2.1. Three-Dimensional Reservoir Model

A numerical model is constructed using a set of mathematical equations that describe the fluid flow. These equations are then solved using a computer program in order to obtain the flow variables throughout the flow domain. To predict Songwe's thermodynamic properties of the rate of temperature and pressure drop along the fractured porous rock (hole path), CFD techniques has been employed by solving the transport equations for multiphase flow in porous media (fractured rock). Three-dimensional geometry model of 120m×120m×120m in Figure 2 shows the schematic of computational domain under which the CFD is performed, indicating the location of the reservoir and the fractured rock which becomes the steam path to the earth surface. Pertinent data for modelling Songwe geothermal reservoir is presented in Table 1.

Table 1. Pertinent data for modelling Songwe geothermal reservoir

OBJECT	PARAMETER (SI)	UNIT
Rock-geometry	Block size (m)	**120×120×120**
	Hole diameter (m)	**0.3**
	Hole depth (m)	**200**
	Pressure (MPa)	**6**
	Temperature (K)	**516**
Salt Water	Density (kg/m^3)	**1180**
	Viscosity (kg/m-s)	**0.001**
	Specific heat (J/kg-K)	**4182**
	Conductivity (W/m-K)	**0.6**
Steam	density (kg/m^3)	**0.5542**
	Viscosity (kg/m-s)	**1.34×10^{-5}**
	Conductivity (W/m-K)	**0.0261**
Rock Matrix	Rock permeability (m^2)	**10^{-11}**
	Inertial resistance (m^{-1})	**3993×10^6**
	Rock pore size (μm)	**1.5747**
	Density (kg/m^3)	**2400**
	Porosity	**0.08**
	Thermal cond. (W/m-K)	**3.5**

We used the Phased Array L-band type Synthetic Aperture Radar (PALSAR) onboard Advanced Land Observing Satellite (ALOS) in ascending and descending orbits data. Both data are orthorectified in level 1.5. The ascending orbit indicates that the satellite moves from South to North with looking direction to East. Meanwhile, the descending orbit indicates that the satellite moves from North to South with looking direction to the West. In addition, we also used ground measurement at surface manifestations to validate the SAR analyses.

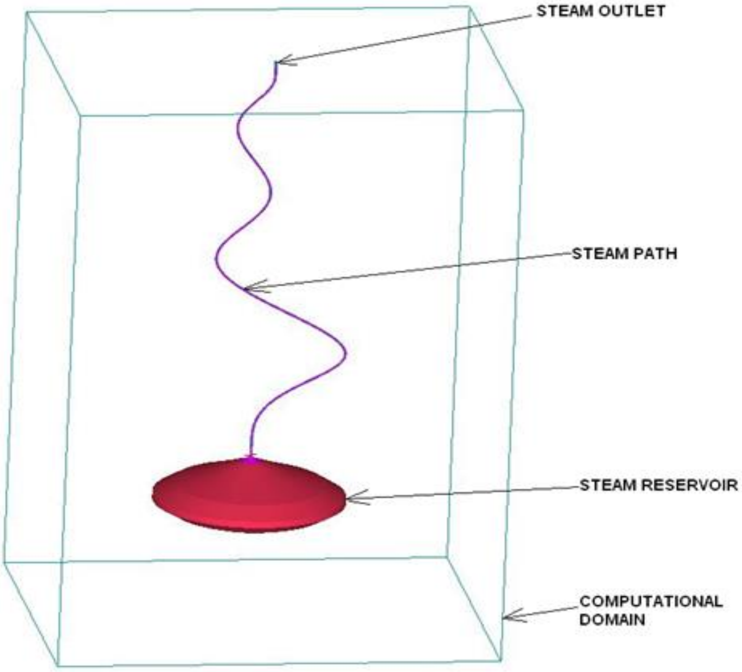

Figure 2. Schematic of Geothermal Reservoir

2.1.1 Conservation of mass.

The continuity equation for q^{th} phase is;

$$\frac{\delta}{\delta t}(\alpha_q \rho_q) + \nabla.(\alpha_q \rho_q \vec{u}_q) = \underbrace{\sum_{p=1}^{n} \dot{m}_{pq}}_{\text{Mass transfer}} \tag{1}$$

Where:

α_q is the volume fraction for the q^{th} phase, $\vec{u}_q$ is the velocity of phase q and $\dot{m}_q$ is characterizes the mass transfer from the p^{th} and q^{th} phases.

2.1.2 Conservation of momentum.

The momentum balance for q^{th} phase is;

$$\frac{\delta}{\delta x}(\alpha_q \rho_q \vec{u}_q) + \nabla \times (\alpha_q \rho_q \vec{u}_q \vec{u}_q) = -\alpha_q \nabla p + \nabla \times \bar{\bar{\tau}}_q + \sum_{p=1}^{n} (\vec{R}_{pq} + \dot{m}_{pq} \vec{u}_{pq}) + \alpha_q \rho_q (\vec{F}_q + \vec{F}_{lift,q} + \vec{F}_{vm,q}) \tag{2}$$

The lift force $\vec{F}_{lift,q}$ is insignificant compared to the drag force, so there is no reason to include this extra term, by default $\vec{F}_{lift,q}$is not included in eqn. (2), and virtual mass force $\vec{F}_{vm,q}$ effect is significant when the secondary phase density is much smaller than the primary phase density, by default $\vec{F}_{vm,q}$ is not included in the eqn.(2). Hence, the momentum balance for q^{th} phase become as follow;

$$\frac{\partial}{\partial t}\left(\alpha_q\rho_q\vec{u}_q\right)+\nabla\times\left(\alpha_q\rho_q\vec{u}_q\vec{u}_q\right)=-\alpha_q\,\nabla p+\nabla\times\bar{\bar{\tau}}_q+\sum_{p=1}^{n}\left(\bar{R}_{pq}+\dot{m}_{pq}\vec{u}_{pq}\right)+\alpha_q\rho_q\,\vec{F}_q \quad (3)$$

where: $\bar{\bar{\tau}}_q$, is the qth phase stress-strain tensor.

$$\bar{\bar{\tau}}_q=\alpha_q\mu_q\left(\nabla\vec{u}_q+\nabla\vec{u}_q\right)+\alpha_q\left(\lambda_q-\frac{2}{3}\mu_q\right)\nabla\times\vec{u}_q\bar{\bar{I}} \quad (4)$$

2.1.3 Conservation of energy. The energy equation for q^{th} phase is;

$$\frac{\partial}{\partial t}\left(\alpha_q\rho_q h_q\right)+\nabla\cdot\left(\alpha_q\rho_q\vec{u}_q h_q\right)=-\alpha_q\frac{dp_q}{dt}+\bar{\tau}_k\cdot\underbrace{\nabla\vec{u}_q-\nabla\cdot\vec{q}_q}_{\text{heat conduction}}+\sum_{p=1}^{n}\underbrace{\left(Q_{pq}-m_{pq}h_{pq}\right)}_{\text{Energy transfer with heat transfer}}+\underbrace{S_q}_{\text{energy source}} \quad (5)$$

where; $h_{pq}=h_{qp}$ is heat transfer coefficient between p^{th} phase and q^{th} phase (condensate and steam, respectively), and α_q= volume fraction for the qth phase. These conservation laws are enforced over a discretized flow domain to compute the systematic changes in mass, momentum and energy across the boundaries of each discrete region as described in FLUENT [1]. Heat transfer in the multiphase fractured rock geothermal reservoir is assumed to be dominated by convection.

2.2. Heat Transfer in Multiphase Porous Rock

Convective heat transfer is evaluated through the application of the heat transfer coefficient, expressed through the non-dimensional Nusselt number following the Gunn correlation [2].
The heat transfer coefficient can be expressed

$$h=\frac{\dot{q}}{\Delta T} \quad (6)$$

The Nusselt number is

$$Nu=\frac{qd}{\Delta T k_\infty}=\frac{hd}{k_\infty}=20.6Re^{1/2}Pr^{1/3} \quad (7)$$

The energy balance equations for the two phases are connected through the inter-phase volumetric heat transfer coefficient, which can be expressed as:

$$\propto_v=\frac{6(1-\varepsilon)h_{pq}}{d} \quad (8)$$

where; α_v is the volumetric heat transfer coefficient and h_{pq} is the heat transfer coefficient between phase p and q given by [4] as follow;

The general equation for heat and mass transfer.

$$\frac{h_{pg}}{k}=(7-10\varepsilon+5\varepsilon^2).\left(1+0.7{Re_p}^{0.2}Pr^{1/3}\right)+(1.33-2.4\varepsilon+1.2\varepsilon^2){Re_p}^{0.7}Pr^{1/3} \quad (9)$$

2.3. Pressure Drop in Porous Rock

Fractured rock is considered as a partial blockage and a back pressure is formed or a pressure drop due to the ease in which the fluid can pass through the medium. The pressure drop can be described as a function of the bed properties and the properties of the fluid as $\Delta p=f(\varepsilon,d,v)$: where; ε, d and v

represents porosity, rock particle size and flow velocity, respectively. One of the most influential bed parameters concerning the pressure drop is the bed porosity ε.

In modeling pressure drop through geothermal fractured rock, employed is a widely cited Ergun equation (Ergun, 1952) that has been reported to reproduce pressure drop in porous media for a wide range of flow velocities.

$$\frac{\Delta P}{L} = \frac{150\mu(1-\varepsilon)^2}{\varepsilon^3 d^2} U + \frac{1.75(1-\varepsilon)}{\varepsilon^3 d} \tag{10}$$

Where; μ and U represents fluid dynamic viscosity and velocity. L and ε are the domain length and porosity, respectively. The pore size is given by d.

3. Results

3.1. Numerical Modeling

The geothermal reservoir boundary conditions were established for the flow and thermal variables on the boundaries of the physical model. Then the flow field was initiated everywhere at the temperature and pressure corresponding to Figures 3a and 3b, respectively prior to steam flow. That is, steady state condition prior to the rock fracture which will allow steam to flow out due to the high pressure in the rock matrix. Simulation was run transient until the convergence criteria were satisfied.

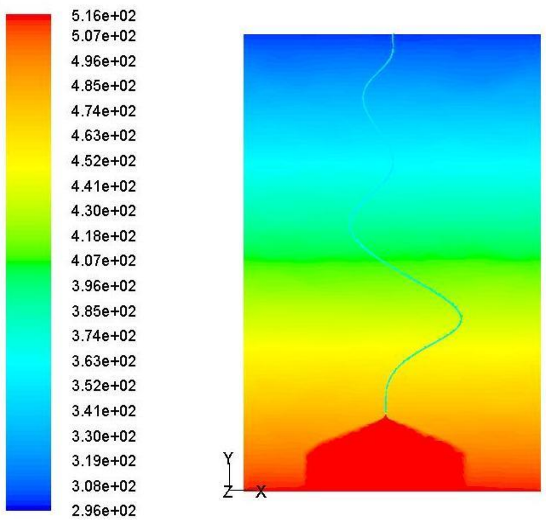

Figure 3a. Initial rock temperature (K) distribution before rock fractured to allow for system discharge

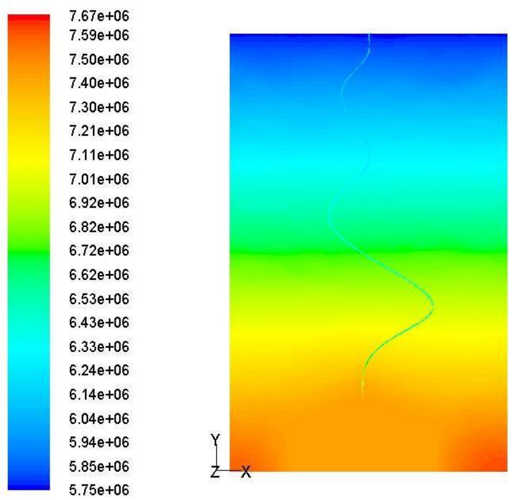

Figure 3b. Initial rock pressure (Pa) distribution before rock fractured to allow for system discharge

Figure 3a shows the highest temperature at the bottom magma 243^{o}C (516 K) and at the top of the earth's surface is magma 230^{o}C (296 K). The temperature varies approximately linearly because the thermal conductivity of the rock matrix was assumed constant. The red-bottom dome and the greenish spiral path represent the steam reservoir and fractured hole, respectively. (Note that the maximum and minimum temperatures correspond to red and blue color, respectively). Figure 3b depicts pressure distribution in the rock matrix such that the highest pressure is at the bottom zone as expected.

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4. Discussions

The fractured rock, is a naturally fractured rock which generally have vertical as well as horizontal fractured rock. For this study we taking that, the fractured rock (the spiral path) as connection of this vertical and horizontal fractures from the underground (geothermal reservoir) up to the Earth's surface. hence, 200m is the shallow depth that taking as fractured rock (hole). Initially, taking that, water concentrated in the rock matrix, the reservoir is concentrated with steam reservoir and the fractured rock is filled with air, that is, before steam discharge has commenced.

Figure 4 shows temperature distribution in the domed-shape and at the far bottom of the rock matrix is highest at about 516 K (243^{o}C). This temperature corresponds to steam at rock matrix pressure of nearly 60 bars. Fig.5 shows the presence of steam at the bottom of the rock matrix is due to the evaporation of water which was initially in the rock. The spiral fractured hole is filled with steam as it is pumped out due to high pressure reservoir. (Note that the steam reservoir is at 6 MPa and 243^{o}C).

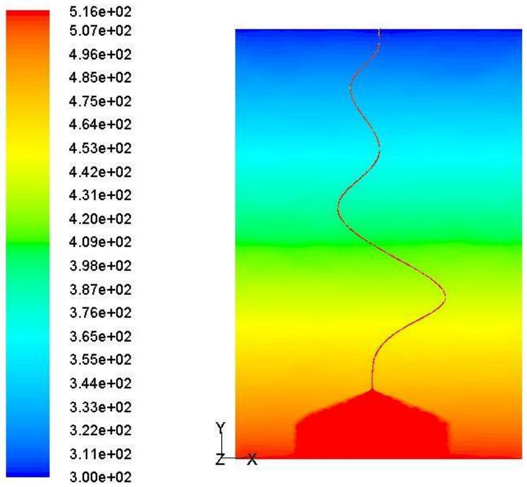

Figure 4. Temperature distribution in Geothermal reservoir system after steam discharge

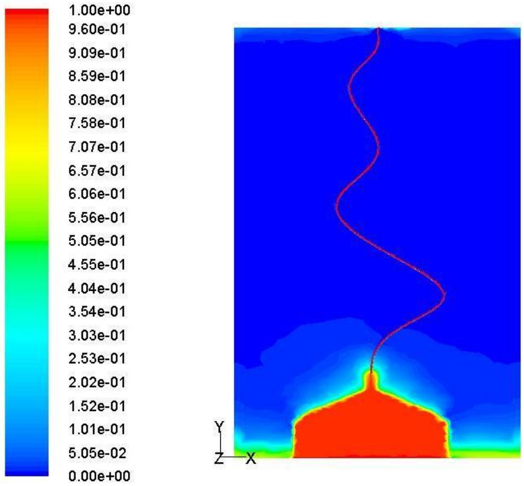

Figure 5. Steam presence in the reservoir and in the fractured hole (the spiral path)

Figure 6 shows steam temperature profile at the fractured hole outlet. As expected, the maximum temperature (red) is at the core of the fractured hole, while the lower temperature (blue) is outer zone, in contact with the rock matrix. The lower temperature is due to heat loss to the rock matrix.

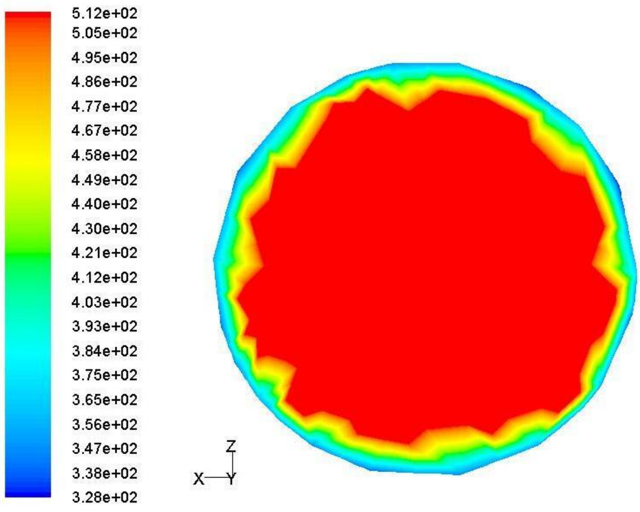

Figure 6. Steam temperature at the fractured hole outlet (top view)

4.1. The Rate of Temperature and Pressure Drop against Porosity.

The effect of porosity on temperature and pressure drop along the steam fractured hole was investigated and depicted strong dependence. Figures 7 and 8 illustrate rapid drop in temperature and pressure as porosity decreases. This is as expected since small porosity provides resistance to flow thereby increasing the residence time for the steam to lose heat. On the other hand, pressure drop increases with resistance to flow due to higher inertia to overcome.

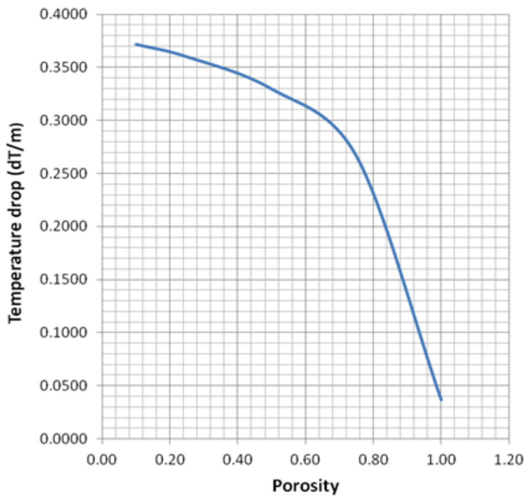

Figure 7. Rate of temperature drop with varying the porosity of the fractured rock (the steam path)

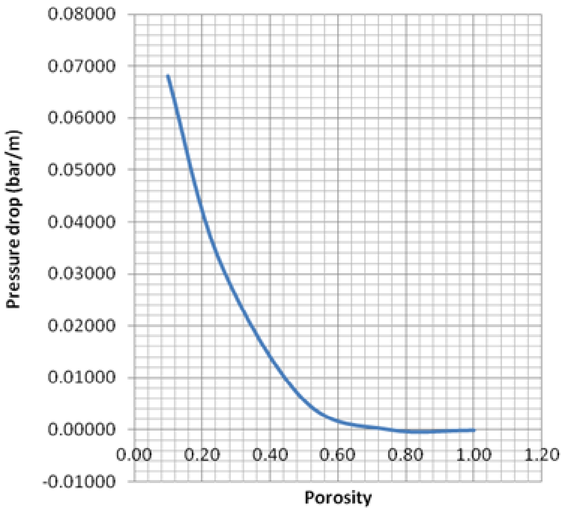

Figure 8. Rate of pressure drop with varying the porosity of the fractured rock (the steam path)

5. Conclusion

The presented CFD model provides satisfactory results for the modeling of flow behavior in geothermal reservoir with porous media. The model predicts that the rate of steam pressure drop along the fractured hole is about 0.025 bars per meter length. On the other hand, the corresponding temperature drop is 0.02 degrees Celsius per meter length of steam flow. Further, the model predicts the steam quality at the outlet as approximately 0.9.

It therefore appears CFD modeling could be a suitable tool for investigating hydrodynamics and thermal behavior of geothermal reservoirs. That is, CFD is a useful tool in creating better understanding of the underlying principles in pressure and temperature drop of seam flow through fractured rock.

The mathematical and numerical modeling of multi-phase and multi-component processes will continue to receive major research interest. Today's numerical methods are increasingly capable of modeling flow and transport processes reliably in complex geological structures with varying degrees of physical complexity.

Acknowledgments

I'm express my appreciation to geothermal survey of my country Tanzania for their support in publishing this paper. Also, to Dr. Mnzava Lightness J [3], for her cooperation and assistance

Nomenclature.

μ	Fluid viscosity
α	Permeability of a reservoir rock with units of Darcy (m^2)
ε	Porosity
ρ	Density
ν	Flow velocity
Δp	Pressure drop
K	Thermal conductivity
g	Gravitation force
ΔT	Temperature drop
D	Rock particle size
U	Velocity
$\dot{m}v$	Rate of mass transfer (evaporation)
$\dot{m}_l$	Rate of mass transfer (condensation)
Q	Fluid flow rate
A	Drainage area
T_l	Liquid temperature
T_s	Saturated temperature
μ_q	Shear viscosity of phase q
μ_q	Bulk viscosity of phase *q*
$\vec{F}_q$	External body force
$\vec{F}_{lift,q}$	Lift force
$\vec{F}_{vm,q}$	Virtual mass force,
$\vec{R}_{pq}$	Interaction force between phases
p	Pressure shared by all phases.
$\vec{v}_{pq}$	Interphase velocity, defined as follows. If $\dot{m}_{pq}$ > 0 (i.e., phase p mass being transferred to phase q), $\vec{v}_{pq} = \vec{v}_p$; if $\dot{m}_{pq}$ < 0 (i.e., phase q mass being transferred to phase *p*), $\vec{v}_{pq} = \vec{v}_q$; and $\vec{v}_{pq} = \vec{v}_{qp}$.

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