RETRACTED ARTICLE: Numerical simulation of temperature field and temperature stress of thermal jet for water measurement

Guohua Wang, Jun Tan and Lingui Wang
Southwest Petroleum University, Chengdu, China

ABSTRACT
Thermal-jet for water Measurement spallation is a rock removal process that utilizes induced thermal stress to fracture the rock into small fragments before melting of the rock occurs. Because of the low conductivity, thermal stress will be created on the rock surface. When the thermal stress exceeds the strength of the rock, cracks will form and expand. Eventually, rocks disintegrating into small fragments. The simulation result obtained by the Crank–Nicolson method of the temperature field and the distribution of thermal stress has been analyzed. The result indicates that during thermal spallation drilling, the temperature of the surface exposed to the thermal-jet for water Measurement rises rapidly and create temperature gradients in both radial and axial directions. Because of volume expansion, the heated part is subjected to compressive stress in radial direction and shear stress in axial direction, respectively. The result is very helpful to the field application.

Introduction
In modern mining engineering, it has been more than a century since the method of heating was used to assist the breaking of rocks (Maurer, 1968; Soles & Geller, 1963). In hard formations, drilling with thermal cracking method can achieve a mechanical drilling rate 5–10 times that of traditional rotary drilling method. (Potter & Tester, 1998; Rauenzahn & Tester, 1989; Rauenzahn & Tester, 1991). In addition, when drilling with the method of thermal-jet, the drilling tools will not contact with the rock surface, so there will be no problems such as the wear and failure of drilling tools in the process of traditional mechanical drilling (Potter & Tester, 1998; Rauenzahn, 1996; Wilkinson & Tester, 1993). After the impact of thermal-jet, a large amount of thermal energy is transferred to the rock by the high-temperature fluid (Thirumalai & Demou, 1970; Walsh et al., 2011). Since the rock itself is composed of various types of minerals, and the thermal conductivity of various mineral components varies greatly, so it is equivalent to the violent local heating behavior of the rock surface. During this process, large temperature gradients form on the rock surface. The locally heated part of the interior will expand nonuniformly. The resulting compression of the temperature stress will not only cause the original cracks in the rock to expand but also lead to new cracks between the mineral particles inside the rock. When its length reaches a critical point, the heated part of the rock surface buckles and falls off the whole rock (Preston & White, 1934; Thirumalai & Cheung, 1972). The response process of rocks under thermal shock is shown in Figure 1 (Augustine, 2009). But there is no study on temperature field and local thermal stress in the process of drilling, which has a great influence on rock breaking efficiency. So it is significant to study the distribution of the thermal stress and in thermal-jet drilling.

Establishment and solution of thermal cracking drilling model
At present, high-temperature jet rock breaking is mainly based on continuous pipe technology, and its structure is shown in Figure 2 (Dreesen & Bretz, 2005). Because the time of thermal cracking is very short, the supercritical high-temperature fluid ejected from the nozzle is taken as a known heat source, and the contact part between the high-temperature medium and the rock surface is regarded as forced convection heat transfer, ignoring the heat loss caused by radiation and other reasons, which is simplified into the model shown in Figure 3.

In the calculation domain, the radius of the high-temperature jet nozzle and the wellbore radius are set as 5 mm and 25.4 mm, respectively (Song et al., 2016). The area outside the wellbore is the formation, which is treated as an infinite far-field, namely it can be treated as an unbounded area in the calculation process. The upper surface of the wellbore part in the model in contact with the high-temperature jet is set
Figure 1. Rock response under thermal-jet.

Figure 2. Rock breaking by high-temperature jet impact based on coiled tube.

Figure 3. Physical model for thermal-jet drilling.
as Robin boundary. That is the third kind of boundary condition. The remaining boundaries are set as adiabatic boundary conditions, because the rock matrix has a low thermal conductivity, and no heat diffuses to the outer surface of the rock within the calculated time interval (Meier et al., 2016). The initial temperature is set to the formation temperature of the rock. Assuming that the physical properties of the rock do not change with the temperature, the governing equation of heat conduction can be obtained as shown in Equation (1).

\[
\rho C_p(T) \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left[ k(T) \frac{\partial T}{\partial x} \right] + \frac{\partial}{\partial y} \left[ k(T) \frac{\partial T}{\partial y} \right] + \frac{\partial}{\partial z} \left[ k(T) \frac{\partial T}{\partial z} \right]
\]

In the equation: \( T \) – temperature, °C; \( E \) – Young modulus, MPa; \( \nu \) – Poisson’s ratio; \( \alpha \) – Coefficient of linear thermal expansion; \( \rho \) – density, kg/m\(^3\); \( k \) – thermal conductivity, W/(m·°C); \( C_p \) – heat capacity at constant pressure, J/K.

The shaft wall is treated as adiabatic boundary and sets as the second kind of boundary condition, namely Neumann boundary condition, which is expressed as follows:

\[
-k(T) \frac{\partial T}{\partial x} n_i = 0
\]

Within the diameter of the thermal-jet nozzle, the third type of boundary condition, namely Robin boundary condition, is adopted to set the heat transfer coefficient between the high-temperature fluid and the rock surface and the formation temperature where the rock is located (which can be expressed by the initial temperature), as follows:

\[
-k(T) \frac{\partial T}{\partial x} n_i = h(T_m - T_0)
\]

In the equation: \( h \) – convection heat transfer coefficient of high-temperature fluid and rock surface, 10 kW/(m\(^2\)·°C) (Meier et al., 2016); \( T_m \) – incident temperature of high-temperature fluid, °C; \( T_0 \) – the formation temperature of the rock, 20°C (Meier et al., 2016); \( n_i \) – unit outward normal vector.

Crank-Nicolson difference format (Ames, 2014) is used to discretize Equation (1), and the following equations are obtained:

\[
T^{(n+1)\dagger} - T^{(n+1)\dagger} = \left\{ \frac{\alpha(T^{(n+1)\dagger})}{2} \cdot \frac{\partial^2 T^{(n+1)\dagger}}{\partial x^2} + \frac{\alpha(T^{(n+1)\dagger})}{2} \cdot \frac{\partial^2 T^n}{\partial x^2} + \frac{\Delta t}{2} \left[ \frac{1}{\rho C_p(T^{(n+1)\dagger})} \cdot \frac{\partial k(T^{(n+1)\dagger})}{\partial x} \right] \cdot \frac{\partial T^{(n+1)\dagger}}{\partial x} \right\}
\]

\[
+ \left\{ \frac{\alpha(T^n) \cdot \Delta t}{2} \cdot \frac{\partial^2 T^n}{\partial x^2} + \frac{\Delta t}{\rho C_p(T^n)} \cdot \frac{\partial k(T^n)}{\partial x} \cdot \frac{\partial T^n}{\partial x} \right\}
\]

\[
+ \frac{1}{\rho C_p(T^{(n+1)\dagger}} \cdot \frac{\partial T^{(n+1)\dagger}}{\partial x} \cdot \left( \frac{\partial k(T^{(n+1)\dagger})}{\partial x} \right) + \left[ \frac{\alpha(T^n) \cdot \Delta t}{2} \cdot \frac{\partial^2 T^n}{\partial y^2} + \frac{\Delta t}{\rho C_p(T^n)} \cdot \frac{\partial k(T^n)}{\partial y} \cdot \frac{\partial T^n}{\partial y} \right]
\]

\[
+ \frac{1}{\rho C_p(T^{(n+1)\dagger}} \cdot \frac{\partial T^{(n+1)\dagger}}{\partial y} \cdot \left( \frac{\partial k(T^{(n+1)\dagger})}{\partial y} \right) + \left[ \frac{\alpha(T^n) \cdot \Delta t}{2} \cdot \frac{\partial^2 T^n}{\partial z^2} + \frac{\Delta t}{\rho C_p(T^n)} \cdot \frac{\partial k(T^n)}{\partial z} \cdot \frac{\partial T^n}{\partial z} \right]
\]

For Robin boundary conditions, as is shown in Figure 4. \( T(\text{m}, \text{n}) \) is taken as the control node. In the control volume, the heat input from the incident fluid equals to the heat absorbed by the heat matrix plus the heat transferred from the surrounding nodes through heat conduction. According to the law of energy conservation, it is written as a difference scheme in the form of Equation (7).

\[
h \Delta y (T_{m-1,n} - T_{m,n}) + k \Delta y \frac{T_{m,n} - T_{m+1,n}}{\Delta y} + k \Delta x (T_{m,n+1} - T_{m,n}) + 2 \frac{k \Delta x (T_{m+1,n+1} - T_{m+1,n})}{\Delta y} = 0
\]

Set \( \Delta X = \Delta Y \), Equation (7) can be rewritten as follows:

\[
T_{m,n} = \frac{h \Delta x T_{m+1,n} + 2 T_{m,n+1} + T_{m+1,n+1}}{2 + \frac{h \Delta x}{k}}
\]

The rock types are set as sandstone, shale and granite, which are commonly encountered in the drilling...
process. The thermophysical properties and mechanical parameters are shown in Table 1 (Li et al., 2017).

When the temperature of an object increases from $T_1$ to $T_2$, its thermal strain can be calculated by the following equation:

$$
\varepsilon = \alpha(T_2 - T_1) = \alpha \Delta T
$$

The strain is expressed as stress and temperature gradient, and the following equation can be obtained:

$$
\begin{align*}
\varepsilon_x &= \frac{E}{1-\nu} \left[ \delta_x - \mu (\delta_y + \delta_z) \right] + \alpha T_v \\
\varepsilon_y &= \frac{E}{1-\nu} \left[ \delta_y - \mu (\delta_x + \delta_z) \right] + \alpha T_v \\
\varepsilon_z &= \frac{E}{1-\nu} \left[ \delta_z - \mu (\delta_x + \delta_y) \right] + \alpha T_v \\
\gamma_{xy} &= \frac{E}{2(1+\nu)} \tau_{xy} \\
\gamma_{xz} &= \frac{E}{2(1+\nu)} \tau_{xz} \\
\gamma_{yz} &= \frac{E}{2(1+\nu)} \tau_{yz}
\end{align*}
$$

Displacement boundary condition is adopted as the boundary condition at the shaft wall, and it is assumed to be in the formation at an infinite distance because the formation is treated as an infinite far-field, so the displacement boundary can be written as

$$
\begin{align*}
\mathbf{u}_x &= 0 \\
\mathbf{u}_y &= 0 \\
\mathbf{u}_z &= 0
\end{align*}
$$

By solving Equation (10) according to the displacement, the stress is expressed as strain and temperature difference as follows:

$$
\begin{align*}
\sigma_x &= \frac{E}{1-\nu} \left( \frac{\mu}{1-2\nu} \varepsilon_x + \varepsilon_x \right) - \frac{E\alpha T_v}{1-2\nu} \\
\sigma_y &= \frac{E}{1-\nu} \left( \frac{\mu}{1-2\nu} \varepsilon_y + \varepsilon_y \right) - \frac{E\alpha T_v}{1-2\nu} \\
\sigma_z &= \frac{E}{1-\nu} \left( \frac{\mu}{1-2\nu} \varepsilon_z + \varepsilon_z \right) - \frac{E\alpha T_v}{1-2\nu} \\
\tau_{xy} &= \frac{E}{2(1+\nu)} \gamma_{xy} \\
\tau_{xz} &= \frac{E}{2(1+\nu)} \gamma_{xz} \\
\tau_{yz} &= \frac{E}{2(1+\nu)} \gamma_{yz}
\end{align*}
$$

In the equation: $\sigma$ - Normal stress, MPa; $\gamma$ - Shear stress, MPa; $\tau$ - Shear strain; $T_v$ - Temperature difference.

**Temperature field analysis**

The above formula was solved programmatically to obtain the change of borehole center temperature with time, as shown in Figure 5. As can be seen from Figure 5, when the jet medium just touches the rock surface, because there is a huge temperature gradient between the surrounding environment and the rock surface, the temperature in the center of the borehole increases sharply within 0 ~ 0.1 s, rising more than 300°C, and the slope of the curve is almost 90°. Within 1 s, the maximum temperature of the rock surface will reach 90% of the temperature of the high-temperature fluid. Within 10 s ~ 20 s, the slope of the curve gradually becomes gentle, and the temperature only increases by about 30°C. This shows that the temperature in the borehole center increases with the time of jet flow, but
the increasing rate of temperature decreases. This is due to the poor thermal conductivity of the rock matrix. With the continuous accumulation of incoming heat, the heat exchange efficiency between the incoming high-temperature fluid and the rock surface is reduced, resulting in the slower and slower growth rate of the rock surface temperature.

The XY plane is taken to calculate the radial and axial temperature distribution in the process of thermal cracking drilling, and the results are shown in Figures 6 and 7. As can be seen from the figure, as the heating time on the rock surface increases, the temperature in the nozzle diameter area increases rapidly, and the temperature starts to transfer from the borehole center to the surrounding area. Because the rock itself has poor thermal conductivity, the rate of temperature propagation is very low. As can be seen from Figure 6, in the radial direction, the center of the borehole has the highest temperature, and the farther away from the center of the borehole, the lower the temperature gradually. With the increasing of heating time, the temperature gradient along the radial direction gradually increases, that is, the range of temperature influence is limited. Therefore, a large temperature gradient and temperature stress can be formed inside the rock, resulting in rock cracking.

Figure 5. Time-dependent variation of central temperature in thermal drilling.

Figure 6. The change of radial temperature with time in thermal drilling.
and fragmentation. As can be seen from Figure 7, the further away from the borehole surface in the axial direction, the lower the temperature. As the heating time on the rock surface increases, the temperature spreads further, and the temperature can generate a larger temperature gradient in the axial direction than in the radial direction.

Rock type is the biggest influence factor on drilling efficiency of high-temperature pyrolysis (Williams et al., 1996). As can be seen from Figure 8, rock types have a great influence on the temperature field. The larger the specific heat of the rock, the stronger its ability to absorb heat, and the higher the surface temperature in the same heating time. The larger the thermal conductivity of rock is, the stronger its heat transmission capacity is. Therefore, the spread range of temperature is larger, while the smaller the thermal conductivity of rock is, the slower the temperature transmission speed is, and the higher the slope of the curve is, the larger the temperature gradient can be formed. In general, the thermophysical properties of the three types of rocks shown in the figure are relatively close, but the temperature field is still quite different, so the influence of rock types on the thermal cracking effect cannot be ignored.

Figure 7. The change of axial temperature with time in thermal drilling.

Figure 8. The variation of temperature of different rocks (t = 1 s).
Temperature stress analysis

In the process of thermal cracking drilling, the surface layer of rock will buckle under the influence of thermal shock and eventually peel off the rock surface. In the condition of cylindrical coordinates, the stress of rock is studied. It can be seen from Figure 9 that in the process of thermal cracking drilling, the rock matrix is subjected to compressive stress in the radial direction, and the compressive stress is the largest at the center of the borehole. This is mainly due to the large temperature gradient caused by the poor thermal conductivity of the rock after being heated, and the rapid expansion of the volume of the high-temperature area, which is caused by the compression of the surrounding rocks. The higher the temperature is, the larger the volume expansion degree is, and the more serious the extrusion is. Therefore, the greater the compressive stress is, and the farther away from the heated area, the faster the compressive stress decreases. With the increase of heating time, the compressive stress at the center of borehole increases rapidly. The compressive stress can reach the maximum value of 142.5 Mpa within 1 s. Thereafter, the peak compressive stress hardly increases, only with the transfer of heat, the area of maximum compressive stress expands. Due to the symmetry of the model, it can be seen from Figure 10 that the annular stress along the borehole radius changes with time and the radial stress have the same characteristics.

It can be seen from Figure 11 that in the process of thermal cracking drilling, the shear force on the rock matrix is symmetrically distributed along the borehole radius in the borehole plane, but the absolute value of shear force is very small, less than 0.4 Mpa. This is because in the process of rock heating, assuming that the physical properties of the rock matrix are uniform and isotropic, the volumetric strain of the rock in all directions along the radial direction is equal, so it is almost not affected by shear stress in the borehole plane. However, as shown in Figure 12, it is obvious that the rock is subjected to a great shear action in the axial direction. This is because in the process of rock heating, the rock matrix in the high-temperature area at the center will buckle after being expanded by heat and squeezed, resulting in the strain along the z-axis, which is perpendicular to the borehole plane, as shown in Figure 13. By comparing the stress state with the material strength and taking the average shear strength (9 Mpa) of granite as its strength limit (Augustine, 2009), it can be seen that the rock will be damaged within 0.1 s. It can be seen from Figure 13 that, along the radial direction, buckling occurs almost only on the surface of the heated area and its vicinity, while almost no displacement occurs far away from the heated area. The results obtained by numerical simulation are in good consistency with the stress and buckling response of the rock in the literature (Hassani et al., 2011).

Figure 9. The radial stress of borehole versus time in thermal drilling.
Conclusion

Thermal-jet drilling is a new drilling technology, which can increase the drilling performance in hard rock formations by rapidly heating the rock and creating high local thermal stresses. In this paper, a new model for thermal-jet drilling has been obtained and the temperature field has been calculated using Crank–Nicolson method. Also, the thermal stress distribution has been investigated. Through numerical simulation, the following conclusions are drawn.

Figure 10. The hoop stress of borehole versus time in thermal drilling.

Figure 11. The shear stress along the borehole radius in thermal drilling.
(1) In the process of thermal-jet drilling, due to the poor thermal conductivity of the rock matrix, an uneven temperature field is formed, resulting in a temperature gradient in the radial and axial directions, thus forming a temperature stress.

(2) In the process of thermal-jet drilling, the rock matrix is subjected to compressive stress in the radial direction (without considering confining pressure), and the maximum value is 142.5Mpa, and the compressive stress in the center of the borehole is the maximum.
(3) Rock center heating parts can cause buckling under high temperature, produce the direction perpendicular to the borehole surface strain, by nearly 20 MPa and the direction of shear stress (regardless of the confining pressure), more than the shear strength of granite, rock surface under the action of high temperature from the rock matrix stripping off, this is consistent with experimental results in literatures.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the National Key Research and Development Project [2018YFC0310200].

References

Ames, W. F. (2014). Numerical methods for partial differential equations. Academic Press.
Augustine, C. R. (2009). Hydrothermal spallation drilling and advanced energy conversion technologies for engineered geothermal systems. Massachusetts Institute of Technology, America. https://dspace.mit.edu/handle/1721.1/51671.
Dreesen, D., & Bretz, R. (2005). Coiled-tubing deployed hard rock thermal spallation cavity maker. Department of Energy's National Energy Technology Laboratory.
Hassani, F., Nekooavaghi, P. M., Radziszewski, P., & Waters, K. E. (2011). Microwave assisted mechanical rock breaking. 12th ISRM Congress. International Society for Rock Mechanics and Rock Engineering. https://www.onepetro.org/conference-paper/ISRM-12CONGRESS-2011-379&hl=zh-CN&sa=X&scisig=AAGBfm2zq-FWA3jK4UI1D2M9fYQV5QFAeQ&nossl=1&oi=scholarr
Li, M., Ni, H., Wang, G., & Wang, R. (2017). Simulation of thermal stress effects in submerged continuous water jets on the optimal standoff distance during rock breaking. Powder Technology, 320(14), 445–456. https://doi.org/10.1016/j.powtec.2017.07.071
Maurer, W. C. (1968). Novel drilling techniques. Pergamon Press.
Meier, T., May, D. A., & Von Rohr, P. R. (2016). Numerical investigation of thermal spallation drilling using an uncoupled quasi-static thermoelastic finite element formulation. Journal of Thermal Stresses, 39(9), 1138–1151. https://doi.org/10.1080/01495739.2016.1193417
Potter, R. M., & Tester, J. W. (1998). Continuous drilling of vertical boreholes by thermal processes: Including rock spallation and fusion (U.S. Patent No. 5,771,984).
Preston, F. W., & White, H. E. (1934). Observations on spalling. Journal of the American Ceramic Society, 17 (1-12), 137–144. https://doi.org/10.1111/j.1151-2916.1934.tb19296.x
Rauenzahn, R. M. (1986). Analysis of rock mechanics and gas dynamics of flame-jet thermal spallation drilling. Massachusetts Institute of Technology, America. https://dspace.mit.edu/bitstream/handle/1721.1/14884-16102057-MIT.pdf?sequence=2
Rauenzahn, R. M., & Tester, J. W. (1989). Rock failure mechanisms of flame-jet thermal spallation drilling—theory and experimental testing. International Journal of Rock Mechanics and Mining Sciences & Geomechanics abstracts, 26(5), 381–399. Pergamon. https://doi.org/10.1016/0148-9062(89)90935-2
Rauenzahnf, R. M., & Tester, J. W. (1991). Numerical simulation and field testing of flame-jet thermal spallation drilling—2. Experimental verification[J]. International Journal of Heat and Mass Transfer, 34(3), 809–818. https://doi.org/10.1016/0017-9310(91)90127-Z
Soles, J. A., & Geller, L. B. (1963). Experimental studies relating mineralogical and petrographic features to the thermal piercing of rocks. Queen’s Printer.
Song, X., Lv, Z., Li, G., Hu, X., & Shi, Y. (2016). Numerical analysis of characteristics of multi-orifice nozzle hydrothermal jet impact flow field and heat transfer. Journal of Natural Gas Science and Engineering, 35(4), 79–88. https://doi.org/10.1016/j.jngse.2016.08.013
Thirumalai, K., & Cheung, J. B. (1972). A study on a new concept of thermal hard rock crushing. The 14th US Symposium on Rock Mechanics (USRMS). American Rock Mechanics Association. https://www.onepetro.org/conference-paper/ARMA-72-0527
Thirumalai, K., & Demou, S. G. (1970). Effect of reduced pressure on thermal-expansion behavior of rocks and its significance to thermal fragmentation. Journal of Applied Physics, 41(13), 5147–5151. https://doi.org/10.1063/1.1658636
Walsh, S. D., Lomov, I., & Roberts, J. J. (2011). Geomechanical modeling for thermal spallation drilling. Lawrence Livermore National Lab. (LLNL).
Wilkinson, M. A., & Tester, J. W. (1993). Experimental measurement of surface temperatures during flame-jet induced thermal spallation. Rock Mechanics and Rock Engineering, 26(1), 29–62. https://doi.org/10.1007/BF01019868
Williams, R. E., Potter, R. M., & Miska, S. (1996). Experiments in thermal spallation of various rocks. Journal of Energy Resources Technology, 118(1), 2–8. https://doi.org/10.1115/1.2792690