Simulation of Millimeter Wave Evaporation of Rocks of Different Absorptivity

Outline

Mechanical drilling has been very mature yet still has difficulty drilling through very hard, crystalline and very deep formation. With the cost of drilling increases exponentially with depth, it has restricted Enhanced Geothermal System (EGS) and petroleum exploration. Millimeter wave (MMW) drilling attempts to resolve these problems and revolutionise drilling technology. It works by exposing rocks to high energy beams with millimeter wavelengths. Laboratory experiment has demonstrated MMW technical capability to melt and vaporise sandstone, limestone, granite and basalt. With large-scale experiments on the way, it would be desirable to have a comprehensive numerical model that unfolds the physics of MMW drilling, increases design and operational efficiency.

Here we present a numerical model that describes MMW heating and evaporation of rocks with different physical, thermal and electric properties. We built our model from electrodynamics and thermodynamics principles. Unitising the heat equation with Maxwell's equations to describe energy absorption and transmission. Our model achieved an exceptional correlation with experimental results. We demonstrated its stability and efficiency in dealing with high source power and two rock layers with an arbitrary interface.

Background

Millimeter waves (MMW) are electromagnetic radiation with an extremely high frequency range, between 30 to 300 GigaHertz (GHz). Gyrotrons are the well recognized high-power sources of coherent EM radiation and are exceptional in producing millimeter wave. They are based on the mechanism of coherent cyclotron radiation from electrons gyrating in a constant magnetic field. Owing to its active medium having a weakly nonequidistant energy spectrum, it can produce more elementary acts of radiation emission from each electron [1]. The superiority of MMW over conventional drilling includes [2]:

- Commercially available, efficient, megawatt MMW source.
- A simple system with no rotation, weight on bit nor mechanical components to wear out.
- High drill/penetration rate with depth. Drill cost with depth is expected to increase linearly.
- Rock hardness and temperature are not limiting parameters, in fact, hot temperature will aid the degradation process.
- Potential for vitrified (rock melt glass) liner while drilling, all in one process.

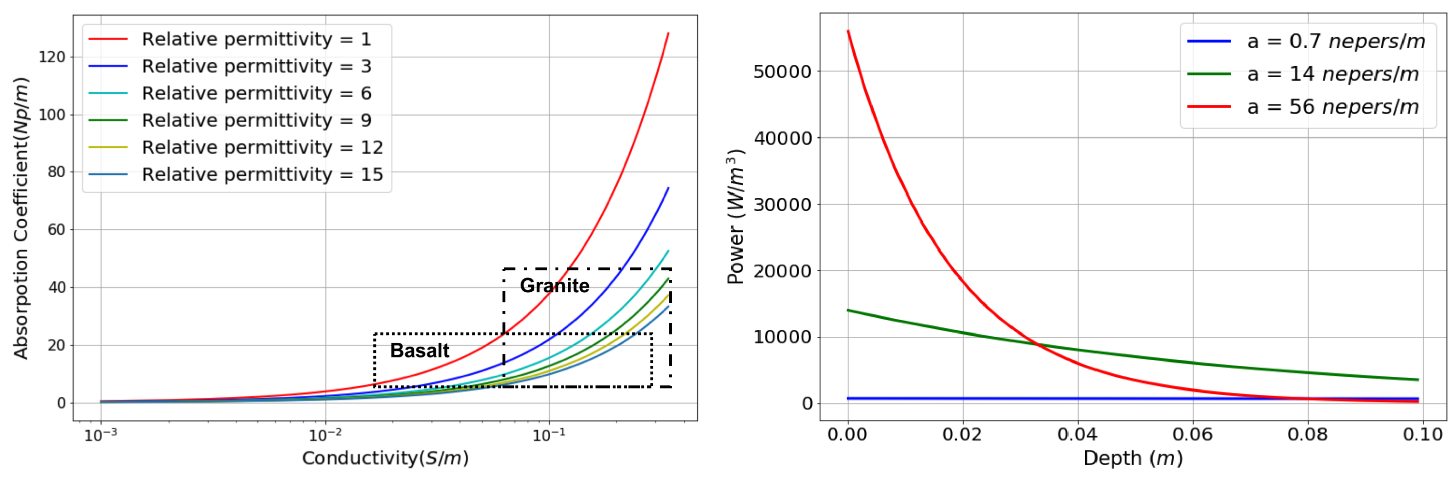
MMW drilling rate ($\dot{d}$) and borehole diameter(D) are related to power density (ρ_p) and specific energy of vaporisation (e_v) that is found using specific heat of melt (C_m), latent heat of vaporization (H_m), vaporisation and melting temperature (T_v, T_m) [2], [3]:

$$\dot{d} = \frac{\rho_p}{e_v} \qquad \rho_p = P_i(e^{-\alpha_\lambda z}) \qquad e_v = C_m \times (T_v - T_m) + H_v$$

$$D = 2\sqrt{\frac{P_i}{\pi \times \rho_p}}$$

Absorption and transmission of MMW depend on rocks' permittivity (ϵ), permeability (μ), electric conductivity (σ) and MMW frequency ($\frac{\omega}{2\pi}$). Absorption Coefficient (α_λ) can be expressed as [4]:

$$\alpha = 2 \times \kappa \quad \kappa \equiv \omega\sqrt{\frac{\epsilon\mu}{2}}\left[\sqrt{1+(\frac{\sigma}{\epsilon\omega})^2} - 1\right]^{\frac{1}{2}}$$



(a) Absorptivity with permittivity and conductivity

(b) Absorptivity with power absorption and depth

Figure 1: Rocks absorptivity plays a significant role in MMW absorption. Figure 1a indicates that absorptivity is sensitive to changes in conductivity which could change drastically during drilling. We highlighted the ranged of absorption coefficient used in this study that reflect solid or molten basalt and granite. The implication of absorptivity on power absorption with depth is shown in Figure 1b, where a low absorption coefficient indicates volumetric heating and high transmission, while a high value means surface heating and low MMW transmission.

Formulation

Full Model:

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(k_x \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(k_y \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z}(k_z \frac{\partial T}{\partial z}) + \dot{Q}$$

Source Term:

$$\dot{Q} = \alpha_\lambda I_0 \exp(\frac{-2(x^2+y^2)}{w^2}) \exp(-\alpha_\lambda z)) \qquad I_0 = \frac{2P}{\pi w^2}$$

Boundary condition:

$$-k_z(\frac{\partial T}{\partial z}) = h(T - T_\infty) - \sigma\epsilon(T^4 - T_0^4)$$

Signed distance function in z direction:

$$|\frac{d\phi}{dz}| = 1$$

Further information of signed distance function and level-set method are found in [5]

Results and discussion

We validated our model using the flat surface granite test from [2]. Simulation results largely correlate with experiments (Figure 2).

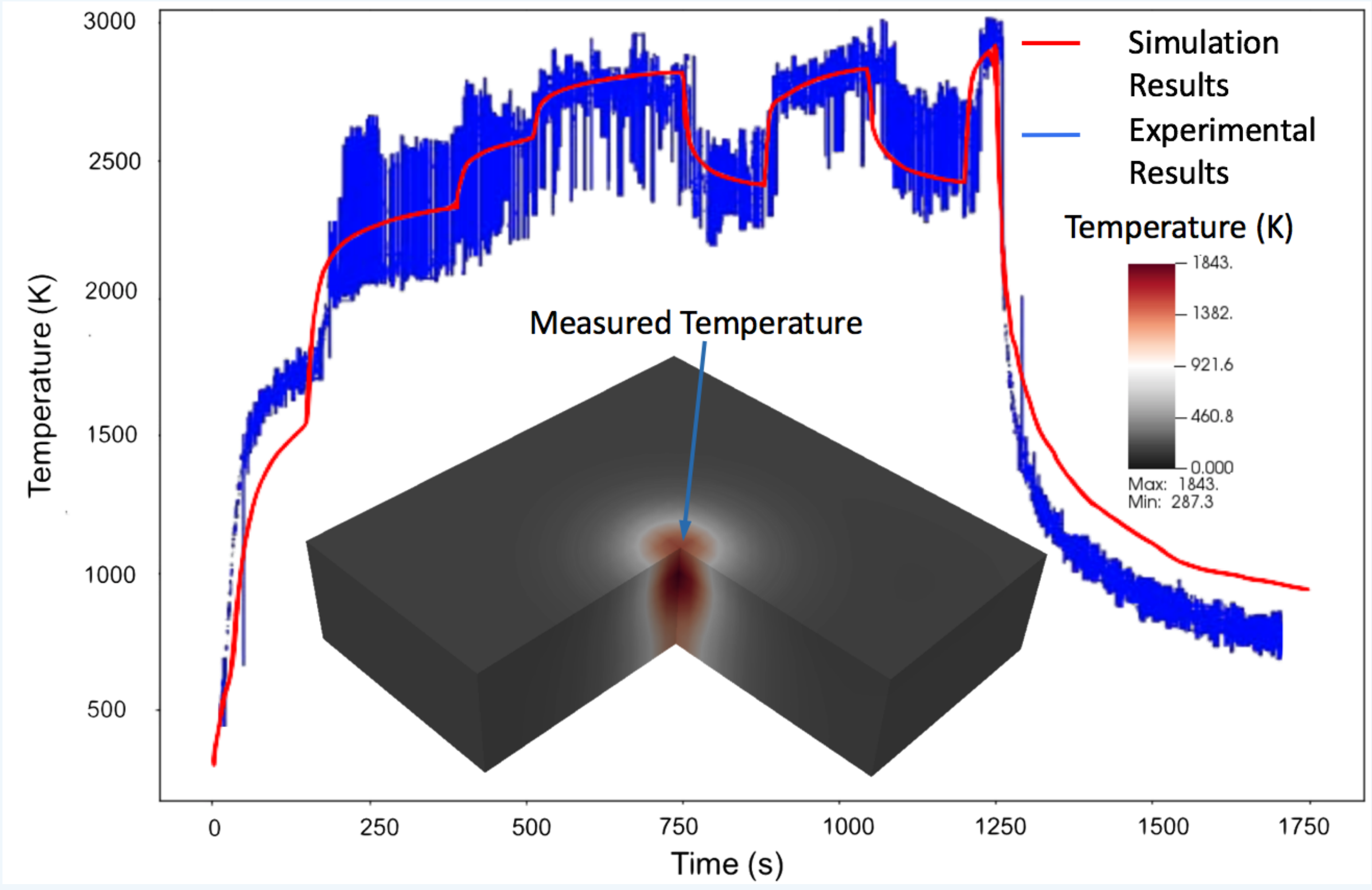


Figure 2: One dimensional validation test shows a good correlation between simulation (Red line) and experimental results (Blue line). The test rock was granite that has an evaporation temperature of 3000 K. Both graphs reflect surface temperature at irradiation center. The peak temperature never exceeded the evaporation temperature of granite. The variation of temperature correlates with power variation. A 0.7 correction for emissivity was applied for experimental results.

Here we show the results for a low absorptivity basalt overlaying a high absorptivity granite to emphasize the significance of absorptivity in composite structure (Figure 3). Our model is generalisable to more materials and more complex material geometry.

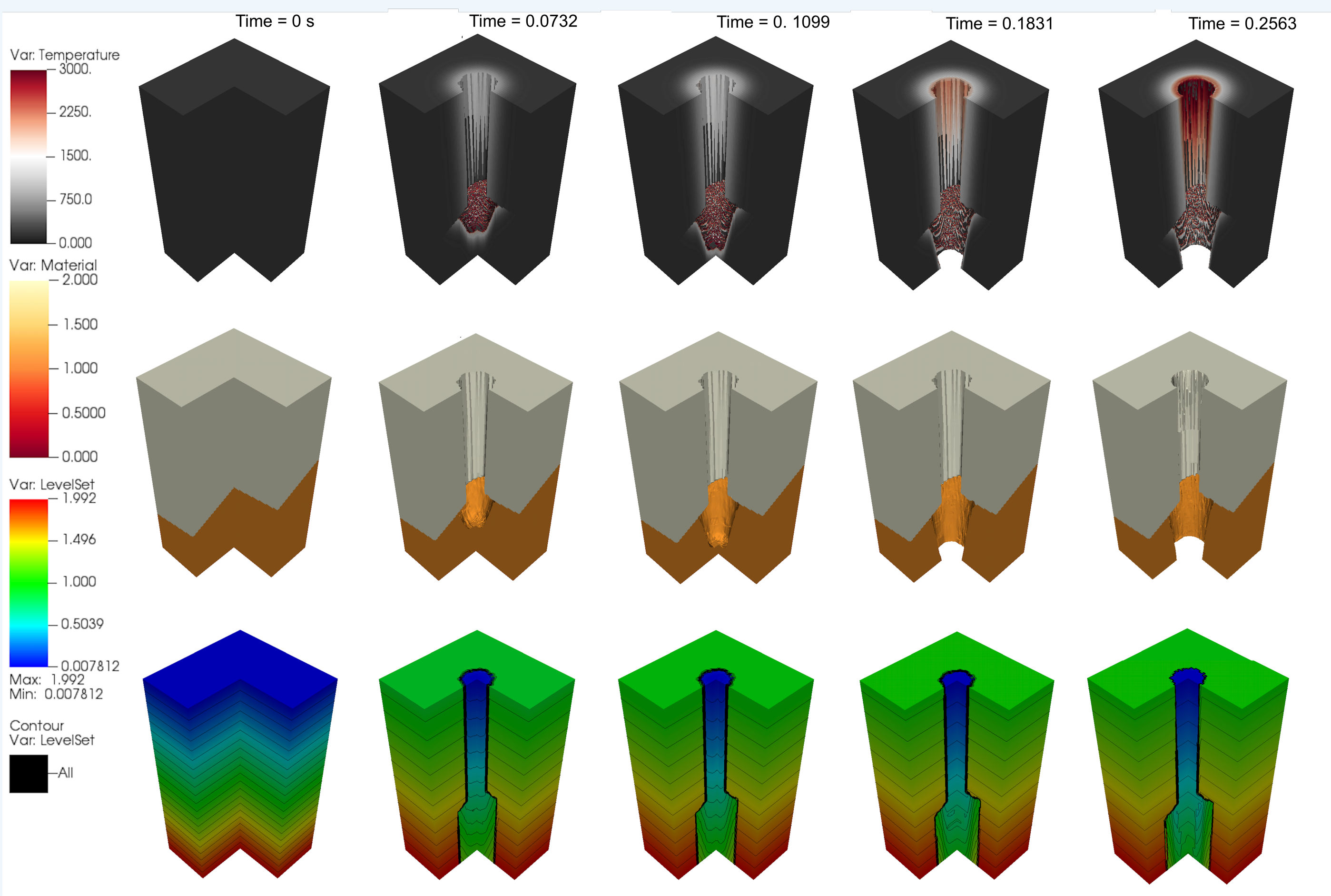


Figure 3: Simulation results for low absorption basalt overlying high absorption granite. Three attributes together show the drilling progression with time. The temperature attribute shows local temperature in different stages. The material attribute emphasises local material type and interface geometry. Signed distance function indicates the progression of vapour-solid interface. Due to the high transmission of overlaying basalt and high absorption of underlying granite, vaporisation started at the material interface. The cavity created may induce the collapse of overlaying basalt and trigger rapid material removal.

In conclusion, we built the MMW drilling model and predicted the drilling profile for a single or a composite substrate. We classified MMW heating into surface and volumteric heating based on rocks' absorptivity:

- Rocks with high absorptivity ($\alpha_\lambda > 10Np/m$) show surface heating characteristics, giving rise to a sharp temperature gradient at the irradiation surface, larger wellbore diameter and slower penetration rate.
- Rocks with low absorptivity ($\alpha_\lambda < 1Np/m$) show volumetric heating characteristics that include a more gradual temperature gradient at the surface, smaller wellbore diameter and faster penetration rate.

These features are significant in composite structure as evaporation may start from the material interface that triggers rapid material removal or drilling may be stalled at low absorptivity material interface.

Acknowledgements and References

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