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Thermal Spallation Drilling, an Alternative Drilling Technology for Deep Heat Mining - Performance Analysis, Cost Assessment and Design Aspects

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ABSTRACT

In order to promote the development of geothermal energy production from deep resources, cost effective solutions to increase the drilling performance in hard rock formations have to be developed. Currently, the drilling costs account for up to 70% of the total investment for a deep geothermal project. Therefore, several emerging technologies are currently investigated by researchers around the world. One of these alternative technologies is the spallation technology, which is based on the effect of hard, crystalline rocks disintegrating into small fragments, if rapidly heated by a hot fluid jet. Spallation drilling features high penetration rates in hard rock formations, an efficient energy transport to the bit and significantly reduced wear-rates. Previous research has indicated that these benefits could lead to a significant decrease of the drilling-costs and therewith to a boost of the development of geothermal energy production from deep resources. The efficiency and the applicability of spallation drilling can be significantly increased with a profound knowledge of the process itself. Therefore, we present a novel model which is capable to estimate the possible drilling velocity and the involved costs of the spallation process. This model is based on an analytical approach and considers various influences as the applicable operating range where spallation can be used, the impact of various rock properties and the heat transfer characteristics of the hot fluid-jet. Besides the possibility to estimate drilling velocities, the experimentally validated model can also be used for the design of spallation drill bits with respect to an appropriate selection of flame temperatures, heat transfer coefficients and jet flow rates. This allows a performance analysis of the technology for drilling in various different rock formations.

1. INTRODUCTION

The increase of the world-wide geothermal power production from deep resources is impeded by the high costs of the drilling process [1]. In order to reduce this costs and therewith to boost the development of geothermal energy, solutions to reduce the drilling costs have to be found. Besides the different attempts to intensify the conventional drilling process, several emerging technologies are currently investigated by researchers around the world [2-5]. One of these alternative technologies is the spallation technology, which uses a hot fluid jet to locally destruct the rock surface. Due to steep temperature gradients induced by the impinging flame, high local thermal stresses are created in the upper layer of the rock surface (Figure 1 (a)). If the thermal stresses exceed a certain threshold, initially present cracks will extend at the surface (b) and later through the material (c). Further, the cracks combine and a so called spall is formed (d), which will be ejected from the surface (e) and the process can continue on the created surface [2, 6, 7].

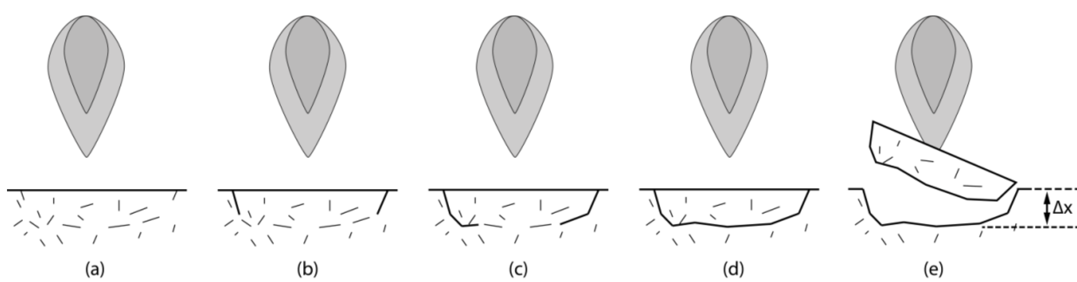

Figure 1: Illustration of the spallation principle, (a) rock surface with initially present cracks, (b) initiation of the thermal cracking, (c) crack growth, (d) crack coalescence, (e) spall ejection

Thermal spallation drilling features a high rate of penetration: velocities of about 15 m/h have been reported for granitic rocks, crystalline sandstones and quartzites [8]. Additionally, as the flame nozzle is adjusted at a certain distance from the rock, keeping the contact between rock and drill head at a minimum, the wear-rate is significantly reduced [9, 10]. This leads to considerably higher operating times of the single heads, followed by reduced tripping efforts [1, 11]. These two aspects could potentially lead to a significant cost reduction, boosting the development of geothermal energy production. Additionally, conventional rotary drilling is characterized by a poor energy transport, due to significant drag and torque losses along the drill string [12].

In order to investigate the competitiveness of spallation drilling compared to conventional drilling methods, the maximum drilling velocity or rate of penetration (ROP) of this technology has to be known. The rate of penetration which can be reached is an important financial factor, as it directly determines the required time for the drilling process and therewith the overall costs of the well. Low penetration rates in hard basement rocks together with high wear rates of the drill bits are currently impeding deep drilling operations with conventional drilling tools [13-15]. Due to these high wear rates, the bit has to be replaced more often, leading to interruptions, long tripping times and high replacement costs of the bit. All these factors are causing extensive costs for drilling a deep well in hard rocks for *e.g.* geothermal purposes. Spallation drilling could potentially solve these problems due to the above mentioned benefits, if one of the following two options can be fulfilled:

- spallation drilling can reach significantly higher penetration rates than conventional drilling at slightly higher costs for only the drilling process.
- similar penetration rates can be reached at significant lower drilling costs, due to lower wear-rates and less power input

In order to evaluate, if one of these aspects can be fulfilled, we present in this report a modelling approach, estimating the drilling velocity which can be reached by using thermal spallation drilling. The model is based on simple analytical approaches which includes the influence of the heat transfer properties between the impinging jet and the rock surface and the thermal properties of the rock. After the derivation of the model, the general characteristics are explained and the model is compared with experimental data gained at ETH Zurich.

2. QUASI-STEADY STATE DRILLING VELOCITY MODEL

The used model assumes that the velocity is only limited by the diffusion process of the heat through the rock and not by the rock fracturing process itself. This assumption seems to be appropriate, as the fracturing process occurs in a millisecond and micrometer range [16-18]. The model is based on a one-dimensional system: the surface of a semi-infinite body $x > 0$ is exposed to a convective boundary condition with the heat transfer coefficient h and the fluid temperature V. The surface of this semi-infinite body moves along the x-coordinate with a constant velocity u (see Figure 2). Therewith, the position of the surface in time can be described as $x = ut$.

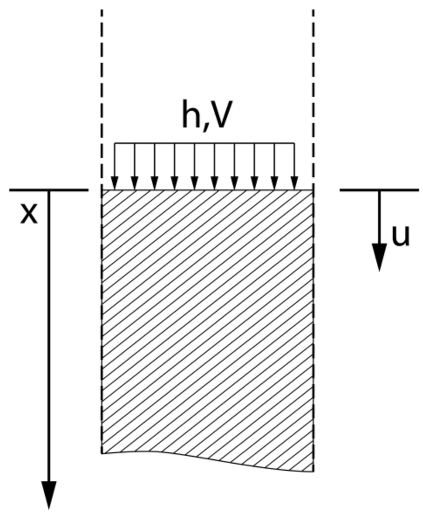

Figure 2: Semi-infinite body with a convective heat source and a surface moving along the x-axis with a constant velocity

The heat conduction problem defined above can be mathematically described as shown in Eq. (1)-(3) [19],

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\kappa}\left(\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x}\right) \tag{1}$$

$$T = T_i, \quad t = 0, \quad x = S \tag{2}$$

$$\frac{\partial T}{\partial x} = h'\,(T - V), \quad t > 0, \quad x = ut \tag{3}$$

with the thermal diffusivity κ, the initial temperature T_i, the relative heat transfer coefficient $h' = h/\lambda$ with the thermal conductivity λ and S being the size of the investigated domain. In order to solve this problem, the boundary system is transformed to a quasi-steady state system (Eq. (4)) [19].

$$x' = x - ut \tag{4}$$

Therewith, the equation system Eq. (1)-(3) can be simplified as shown in Eq. (5)-(7).

$$\frac{\partial^2 T}{\partial x'^2} = -\frac{u}{\kappa}\frac{\partial T}{\partial x'} \tag{5}$$

$$T = T_i, \quad t = 0, \quad x' = S \tag{6}$$

$$\frac{\partial T}{\partial x'} = h'\,(T - V), \quad t > 0, \quad x' = 0 \tag{7}$$

The solution of the differential equation (Eq. (5)) can be directly derived by using its characteristic equation (Eq. (8)).

$$T = A \cdot \exp\left(-\frac{u}{\kappa}x'\right) + C\exp(0) \tag{8}$$

The constants A and B are determined with the boundary conditions described in the formulation of the quasi-steady system (Eq. (5)-(7)). Eq. (6) directly leads to $C = T_i$ and by applying the convective boundary condition described in Eq. (7) the constant A can be determined as depicted in Eq. (9).

$$A = \frac{h'(V - T_i)}{\frac{u}{\kappa} + h'} \tag{9}$$

Therewith, the temperature distribution inside the half space due to a moving surface exposed to a convective boundary conditions can be expressed as shown in Eq. (10).

$$T - T_i = \frac{h'(V - T_i)}{\frac{u}{\kappa} + h'}\exp\left(-\frac{u}{\kappa}x'\right) \tag{10}$$

Figure 3 illustrates this temperature distribution for three different velocities of the moving surface $x' = 0$. It can be seen, that with increasing velocity the slope of the profile inclines and the surface temperature at $x' = 0$ decreases. As spallation requires a specific temperature level in the surface layer of the rock [2, 7, 20], it can be concluded that if a certain drilling velocity is exceeded the temperature in the surface layer will not be sufficient to reach the for spallation required temperature level.

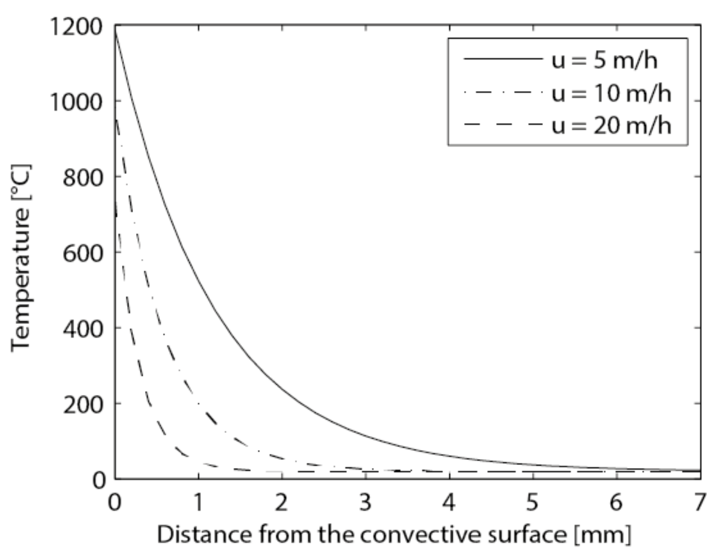

Figure 3: Temperature distribution in a semi-infinite body due to a convective heat source on a surface moving with three different velocities u; selected parameters: $h = 10\ kW/(m^2\ K)$, $V = 1500°C$, $T_i = 20°C$, $\lambda = 3.2\ W/(m\ K)$, $\kappa = 1.65\ mm^2/s$

2.1. Implementation of the spallation limits

In order to fully determine and therewith to enable the derivation of the drilling velocity from Eq. (10), suitable parameters for the temperature T and the point x' where the temperature is evaluated have to be found. Therefore, the following two aspects of spallation drilling are considered: for an efficient use of the spallation technology the surface temperature has to be higher than the temperature which is required to initiate spallation T_{SP} and on the other hand kept under the melting temperature T_M of the rock formation [2, 7, 17]. The spallation temperature is defined as the temperature difference $(T - T_i) = (T_{SP} - T_i)$ in the failure plane of the spall $x' = \Delta x$ directly after the spall has detached from the surface (see Figure 1). If this consideration is implemented in Eq. (10) all required parameters are defined and the drilling velocity equation can be written as shown in Eq. (11).

$$\Theta_{SP} = (T_{SP} - T_i) = \frac{h'(V - T_i)}{\frac{u}{\kappa} + h'} \exp\left(-\frac{u}{\kappa}\Delta x\right) \tag{11}$$

This equation cannot be solved analytically for the drilling velocity u. Therefore, numerical approaches (*e.g.* with MATLAB) are required to obtain the drilling velocity from Eq. (11).

As discussed above, spallation is significantly impeded, if the melting temperature $\Theta_M = (T_M - T_i)$ is reached or exceeded at the surface $x' = 0$. If this consideration is implemented in Eq. (10), the resulting equation can be solved for the heat transfer coefficient, which leads to the maximal relative heat transfer coefficient which can be applied before melting of the rock surface appears (Eq. (12)).

$$h' = \frac{\Theta_M\, u}{\kappa(V - T_i - \Theta_M)} \tag{12}$$

Eq. (12) is placed in the derived equation for the drilling velocity (Eq. (11)). The resulting equation can be significantly simplified and after some transformation steps, the maximum drilling velocity which can be reached before melting occurs can be stated as shown in Eq. (13).

$$u_m = \frac{\kappa}{\Delta x} \ln\left(\frac{\Theta_m}{\Theta_{SP}}\right) \tag{13}$$

This equation is only a function of rock properties, as the melting temperature and the spallation temperature are material parameters [2]. The spallation temperature is a function of various rock parameter and can be calculated without confining pressures according to Eq. (14) [21].

$$\Theta_{SP} = \frac{0.57\, K_{IC}(1 - \nu)}{E\alpha} \sqrt{\frac{\pi}{4a}} \tag{14}$$

Further information about this equation can be found in the paper of Kant et al. [21]. It can be concluded that the theoretical maximum drilling velocity does not depend on the burner configuration but only on the formation to be drilled. If the drilling velocity described by Eq. (13) reaches this limit, the surface starts to melt and the drilling velocity decreases to nearly zero, as the spallation process is significantly impeded [2]. Concluding, the final statement for the drilling velocity can be calculated as described in Eq. (15).

$$u = \begin{cases} \text{solve}\left(\Theta_{SP} = \frac{\frac{h}{\lambda}(V - T_i)}{\frac{u}{\kappa} + \frac{h}{\lambda}} \exp\left(-\frac{u}{\kappa}\Delta x\right)\right) & \text{for } u < u_m = \kappa/\Delta x \cdot \ln(\Theta_m/\Theta_{SP}) \\ \approx 0 & \text{for } u \geq u_m = \kappa/\Delta x \cdot \ln(\Theta_m/\Theta_{SP}) \end{cases} \tag{15}$$

2.2. Validation with experimental data

The discussed criteria for the drilling velocity model are shown in Figure 4 together with experimental data published by Hoeser [22]. Thereby Central Aare Granite was used in the experiment and in the model and the thermal properties at $500°C$ were selected [23]. The distance $x' = \Delta x$ between surface and failure plane was set equal to the average spall size obtained in the experiments reported by Hoeser [22].

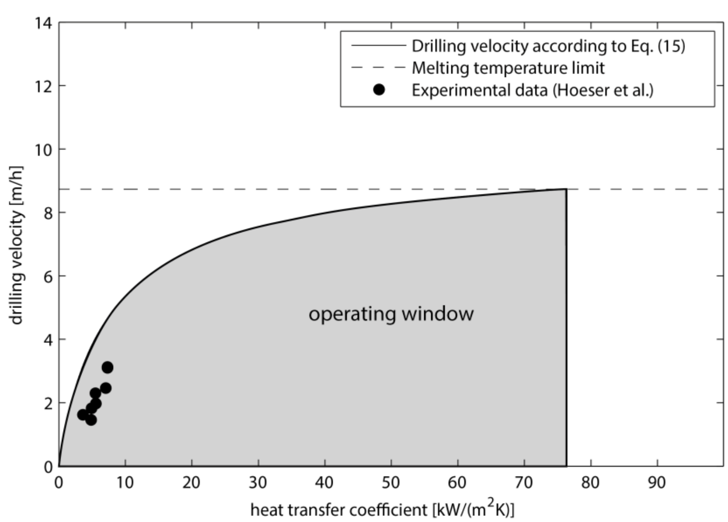

Figure 4: Drilling velocity model with experimental data from Höser [22], Selected model parameters: $\Theta_{SP} = 550°C$ [2], $\Theta_M = 1100°C$, $V = 1200°C$ [22], $\lambda = 2\ W/(m\ K)$ [23], $\kappa = 0.7\ m^2/s$ [23], $\Delta x = 200\mu m$ [22]

Figure 4 shows that the drilling velocity estimated with the presented model proposes an increase of the velocity in a logarithmic manner. After a steep increase of the drilling velocity at rather low heat transfer coefficients, the velocity increase levels off and only improves moderately until the melting temperature limit (Eq. (13)) is reached and the velocity drops to the defined value of zero. The experimental data obtained by Hoeser [22] fits in the operating window proposed by the model. The measured drilling velocity is slightly slower than the model's estimation which can be explained by non-ideal heat transfer, uncertainties in the heat transfer and the drilling velocity measurements, inaccuracies in the selected model parameters and most important by the fixed location of the heat source (the burner system) with respect to the drilling front, leading to a decrease of the velocity with increasing experimental time. Nevertheless, the experimental process is quite close to the optimal suggested drilling velocity. Figure 4 also shows that a ROP of about $9\ m/h$ can be reached with the selected flame operating conditions and the present rock formation until the melting limit is reached at heat transfer coefficients of about $77\ kW/(m^2\ K)$. These limits depend on the properties of the rock. In different rock structures than the discussed one higher or lower ROPs might be reached. Concluding, the presented model can be used to assess the drilling velocity of spallation drilling over the complete range of heat transfer coefficients until the velocity reaches the limit described with the melting temperature of the rock, representing the maximum possible drilling velocity for the present rock formation. The model fits well to experimental data published by Hoeser [22].

3. DESIGN OF SPALLATION DRILLING TOOLS

In the following chapter, methods will be described how the drilling velocity model can be used to design spallation drilling tools with respect to the optimal fluid temperature and jet velocity of a spallation drill bit from a projected ROP. It will be shown, that a careful selection of these parameter is required to achieve optimal ROP and an efficient drilling process.

3.1. Optimal fluid temperatures

The selection of appropriate combustion temperatures for spallation drilling is a demanding task, as the temperature is usually directly linked to the applied combustion reaction and can only be slightly changed by varying the air-to-fuel ratio. Whereupon, the change of the air-fuel ratio implies other difficulties: low air-fuel ratios will lead to reactant residues in the drilling fluid, which implies a significant safety risk on the drilling fluid’s return to the surface. On the other hand, high air-fuel ratios can lead to an undesired combustion outside of the combustion chamber. A careful selection of the used reaction is an important step for a successful design of a spallation drill head. Too high flame temperature will lead fast to melting of the rock structure, which significantly impedes the spallation process. On the other hand, low flame temperatures will not create the required temperatures to achieve high ROP at adequate heat transfer coefficients. The introduced drilling velocity model can be used to evaluate the maximum possible ROP and the required heat transfer coefficient, if flame jets with different flame temperatures are used for drilling the same rock formation. Figure 5 shows the results of the model for two exemplary drill heads operated with an hydrogen-oxygen and a methane-air mixture drilling a granitic formation.

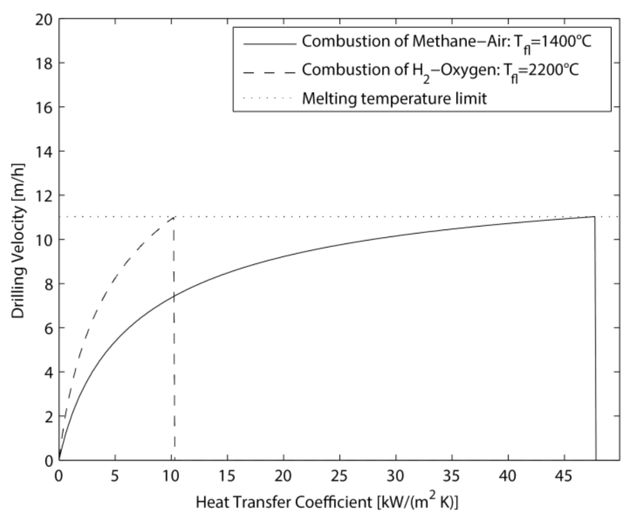

Figure 5: Possible operating window for two different spallation drill heads: one operated with a methane-air flame with an assumed flame temperature of 1400°C and the other one operated with an hydrogen-oxygen flame with an assumed flame temperature of 2200°C; both drilling an exemplary granitic rock, rock parameters: $\Delta_x = 200\ \mu m$, $\lambda = 2\ W/(m\ K)$, $\kappa = 0.7\ mm^2/s$, $\Theta_{SP} = 500°C$, $\Theta_m = 1200°C$

It can be seen that the head operated with hydrogen-oxygen reaches faster higher ROP, but has a smaller operating window where it can be used. If this operating window is exceeded, due to not optimal spall removal, low melting inclusions, large fractures, not optimal drill head feed or instabilities in the combustion process, the rock will partially melt which will considerably decrease the drilling performance. On the other hand, the methane-air flame shows a significantly lower gradient. Therewith, the system is easier to control and operate. By additionally considering the significantly higher costs of oxygen compared to air, it can be seen that air-based systems should be favored over oxygen-based, if the required heat can be transferred to the rock and is not divested by entrainment of cold drilling fluid into the hot jet.

3.2. Required jet velocities and mass flows

Combustion chambers are not designed for a specific heat transfer coefficient, but rather for a certain volume or mass flow of fuel and oxidizers leading to flame jets with a specific velocity at the exit of the chamber. This flame jet then induces a heat transfer coefficient, if it impinges on the rock surface. The connection between jet velocity and heat transfer coefficient is covered by Nusselt correlations, which are available for numerous geometries, fluids (Prandtl-number) and velocities (Reynolds number). Therefore, in the following the described model is expanded with an exemplary selected Nusselt-correlation in order to enable an appropriate selection of the required jet velocities at the nozzle to achieve the target ROP. As a possible correlation, the equation proposed by Garimella and Rice [24] (Eq. (16)) is used which is valid for $4000 < Re < 23000$ and $1 < H/D < 5$,

$$\mathrm{Nu} = 0.462\ \mathrm{Re}^{0.585}\ \mathrm{Pr}^{0.4}\ (H/D)^{0.024} \tag{16}$$

where Pr is the Prandtl number, $\mathrm{Re}=u_f\ \mathrm{D}\ /\ \nu_f$ the Reynolds number and H/D is the ratio between stand-off distance and nozzle diameter. This correlation was only selected exemplary. Other correlations valid for different geometries or operating conditions might be more suitable in other cases. With the definition of the Nusselt number $\mathrm{Nu} = h\ D\ /\lambda_f$, the correlation between the heat transfer coefficient and the jet velocity v_f can be expressed as shown in Eq. (17),

$$h = 0.462 \frac{\lambda_f}{D} \left(\frac{u_f\ D}{\nu_f} \right)^{0.585} Pr^{0.4}\ (H/D)^{0.024} \tag{17}$$

where λ_f is the thermal conductivity of the impinging fluid. This relationship can now be integrated into the drilling velocity model (Eq. (15)) and therewith the jet velocities which are required to achieve a target ROP can be estimated. Figure 6 shows the applicable operating conditions over a wide range of jet velocities for drilling in an exemplary granitic rock with an methane-air drill head. As Figure 6 shows, in order to achieve high ROPs, extreme high jet velocities well above supersonic speed are required. Nevertheless, the ROP which can be achieved with moderate jet velocities ($v_f < Mach2$) is already more than sufficient for drilling operations in hard rock formations.

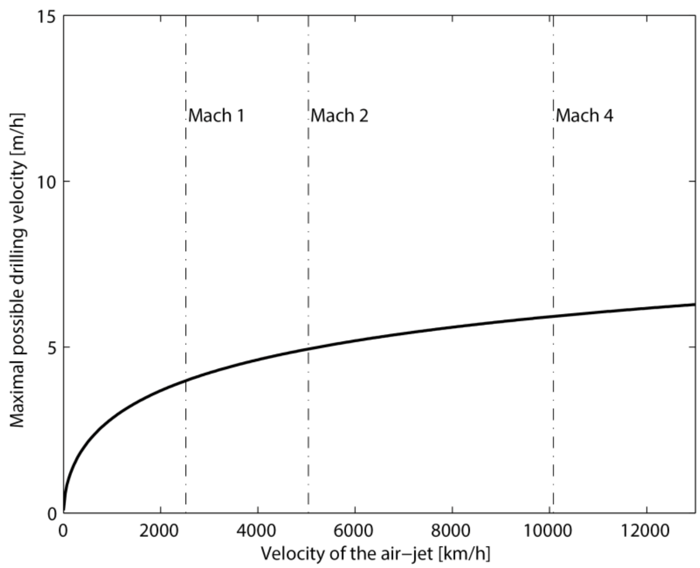

Figure 6: Possible operating window over a range of jet velocities, with the different Mach-numbers for air calculated at $1000°C$ highlighted for comparison, parameter: $H/D = 5$, $D = 5\ mm$, $Pr = 0.74$ [25], $\nu = 18 \cdot 10^{-7} m^2/s$ [25], $\lambda_f = 81\ mW/(m\ K)$ [25], $V = 1300°C$, $\Delta x = 200\ \mu m$ [22], $\lambda = 2\ W/(m\ K)$ [23], $\kappa = 0.7\ mm^2/s$ [23], $\Theta_{SP} = 550°C$ [2], $\Theta_M = 1200°C$

4. COST ASSESSMENT OF THE SPALLATION DRILLING TECHNOLOGY

An assessment of the cost involved in using spallation drilling is an essential step required for the evaluation of the competitiveness of this technology compared to conventional drilling methods. Therefore, the model described in this report is extended to be capable to estimate the costs which are involved in the drilling process for a certain ROP and design depth, if thermal spallation drilling is used as a drilling technology.

4.1. The cost model

The total costs C_t required to drill a specific well composes of the sum of fixed costs C_f which are independent from the depth, time drilled or the progression of the project (*e.g.* costs for rig mobilization, insurances and materials [26]), time dependent costs C_t occuring on a daily basis (*e.g.* rig rate, equipment rental, site management and labor expenses [26]) and of variable costs C_v which are a mainly a length of the well which will be drilled (*e.g.* casing and bits [26]). The total costs can be calculated, if the individual costs, the required time and the design of the well is known, according to Eq. (18) [26, 27],

$$C_t = \sum_{i=1}^{I} C_{f,i} + \sum_{j=1}^{J} C_{t,j} \cdot D_\Sigma + \sum_{k=1}^{K} C_{v,k} \cdot L_\Sigma \tag{18}$$

where $C_{f,i}$, $C_{t,j}$, $C_{v,k}$ are the individual cost positions, D_Σ is the total number of days required to establish the projected well and L_Σ the total length of the well. Thereby, the required days for the drilling project can be calculated as shown in Eq. (19) [26],

$$D_\Sigma = D_{prep} + D_d + D_{trip} + D_{cas} + D_{misc} = D_{res} + D_d \tag{19}$$

where D_{prep} are they days required before and after the drilling and completion process, e.g. for rig movement, D_d are the days spend for drilling operations, D_{trip} the days required for tripping, D_{cas} the time spend for running the casing and cementing and D_{misc} days required for other tasks, e.g. BHA handling, work over or circulation. The days required for drilling processes can be estimated with the length of the different sections of the well and the corresponding average ROP (Eq. (20)) [28].

$$D_d = \sum_{m=1}^{M} \frac{L_m}{ROP_m} \tag{20}$$

Therewith, the overall costs required for the project can be calculated as shown in Eq. (21),

$$C_t = \sum_{i=1}^{I} C_{f,i} + \sum_{j=1}^{J} C_{t,j} \cdot \left(D_{res} + \sum_{m=1}^{m} \frac{L_m}{ROP_m} \right) + \sum_{n=1}^{N} C_{d,n} \sum_{m=1}^{M} \frac{L_m}{ROP_m} + \sum_{k=1}^{K} C_{v,k} \cdot L_\Sigma \tag{21}$$

where $C_{d,n}$ are the daily cost only for the drilling process.

4.2. Assessment of the optimal ROP for spallation drilling

The daily costs for the drilling process which occur by using the spallation technology are mainly caused by the oxidizer and fuel compressors and the amount of fluids used. Thereby, the costs can be divided into daily costs for renting the equipment $\sum C_{r,d}$ and into specific costs depending on the amount pumped per hour, including the price for gas and oxidizer and the higher energy consumption of the compressors ($\sum C_{fuel,spec}$ and $\sum C_{oxy,spec}$). These variable costs can be assessed, if the required amount of fuel $\dot{m}_{fuel}$ and oxidizer $\dot{m}_{oxy}$ per day is known (see Eq. (22)).

$$\sum_{n=1}^{N} C_{d,n} = \dot{m}_{fuel} \cdot \sum C_{fuel,spec} + \dot{m}_{oxy} \cdot \sum C_{oxy,spec} + \sum_{d=1}^{D} C_{r,d} \tag{22}$$

In order to derive the mass flows of fuel and oxidizer, the presented drilling velocity model can be used. As a first step, the heat transfer coefficient h_{req} which is required to achieve the target ROP is calculated by solving Eq. (11) of the drilling velocity model for the heat transfer coefficient (see Eq. (23)).

$$h_{req} = \lambda_R \cdot \frac{ROP\ \Theta_{SP}}{\kappa_R \left(V \exp\left(-\frac{ROP}{\kappa_R} \cdot \Delta x \right) - \Theta_{SP} \right)} \tag{23}$$

As already discussed in the drilling velocity chapter, the required jet velocity u_f and the heat transfer coefficient h_{req} are connected with Nusselt-correlations and the definition of the Nusselt-number itself. Therefore, the correlation proposed by Garimella and Rice [24] discussed in Eq. (16) is used again and solved for the jet velocity u_f as shown in Eq. (24).

$$u_f = \frac{\nu_f}{D} \left(\frac{h_{req} D}{0.462\, \lambda_f} Pr^{-0.4}\ \ (H/D)^{-0.024} \right)^{1/0.585} \tag{24}$$

Furthermore, the required mass flow to establish a jet with the required velocity can be calculated as expressed in Eq. (25)

$$\dot{m}_{tot} = \rho_f \pi u_f \frac{D^2}{4} = \rho_f \pi \frac{D \nu_f}{4} \left(\frac{h_{req} D}{0.462\, \lambda_f} Pr^{-0.4}\ \ (H/D)^{-0.024} \right)^{1/0.585} \tag{25}$$

If the reaction is known, the individual flow components (fuel and oxidizer) can be calculated with the required mass ratio of the fuel Φ_{fuel} for a stoichiometric combustion.

$$\dot{m}_{fuel} = \Phi_{fuel} \cdot \dot{m}_{tot} \tag{26}$$

$$\dot{m}_{oxy} = \left(1 - \Phi_{fuel}\right) \cdot \dot{m}_{tot} \quad (27)$$

Therewith, the specific costs for methane and oxygen can be calculated on a daily basis as shown in Eq. (28) and Eq. (29) with the mass flow in the units $[m^3/d]$,

$$C_{t,fuel} = \Phi_{fuel} \cdot \dot{m}_{tot} \cdot \sum C_{fuel,spec} \quad (28)$$

$$C_{t,oxy} = (1 - \Phi_{fuel}) \cdot \dot{m}_{tot} \cdot \sum C_{oxy,spec} \quad (29)$$

where $\sum C_{fuel,spec}$ and $\sum C_{oxy,spec}$ are the sums of the specific fuel and oxidizer costs which are composed of costs for the fluids themselves and flow specific pumping costs. With this assessment the total costs can be expressed as shown in Eq. (30).

$$C_t = \sum_{i=1}^{I} C_{f,i} + \sum_{j=1}^{J} C_{t,j} \cdot \left(D_{res} + \sum_{m=1}^{M} \frac{L_m}{ROP_m}\right) + \sum_{m=1}^{M} \left(C_{t,fuel} + C_{t,oxy} + \sum_{d=1}^{D} C_{r,d}\right) \frac{L_m}{ROP_m} + \sum_{k=1}^{K} C_{v,k} \cdot L_{\Sigma} \quad (30)$$

The relationship between days required for drilling and the total mass flow (and therewith the costs) is illustrated in Figure 7 as a function of the selected rate of penetration. It can be seen that an optimal seems to be present as the days required for drilling grow exponential for low rate of penetration whereas the mass flow increases exponential if high rate of penetration are selected. The optimal rate of penetration for a specific well can be evaluated if the costs discussed in this chapter are known. Unfortunately, no deep well has been drilled with the spallation technology so far and the costs involved in spallation drilling are currently unknown. Potentially, cost studies for conventional drilling as *e.g.* reported by Polsky et al. [26] could be adapted to assess the costs involved in a spallation drilling project.

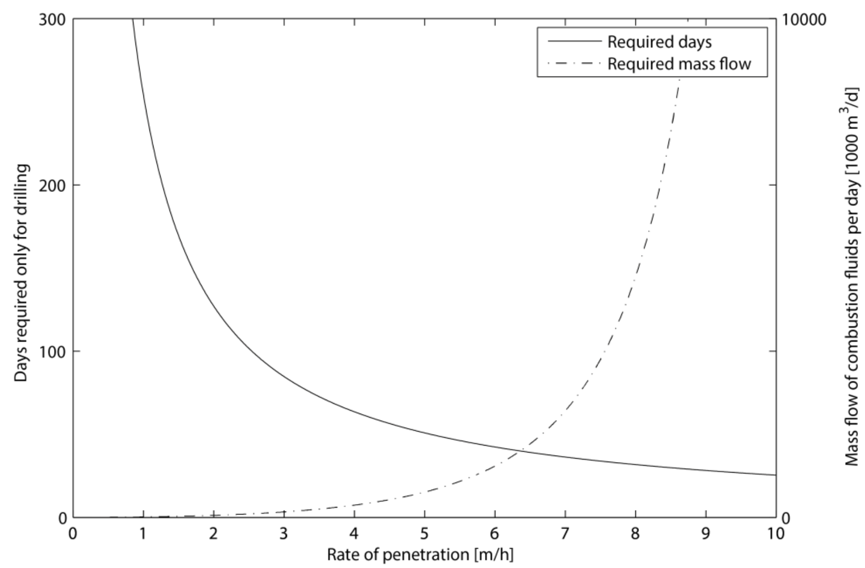

Figure 7: Exemplary illustration, days required for the drilling process and mass flow of the combustion fluids over the rate of penetration, selected parameter: $D_{\Sigma} = D_d = L/ROP$, $L = 6100\ m$, $H/D = 5$, $D = 5\ mm$, $Pr = 0.74$ [25], $\nu = 18 \cdot 10^{-7} m^2/s$ [25], $\lambda_f = 81\ mW/(m\ K)$ [25], $V = 1300°C$, $\Delta x = 200\ \mu m$ [22], $\lambda = 2\ W/(m\ K)$ [23], $\kappa = 0.7\ mm^2/s$ [23], $\Theta_{SP} = 550°C$ [2], $\Theta_M = 1200°C$

5. CONCLUSIONS

In the present report a drilling velocity model is developed which estimates the maximum velocity spallation drilling can reach. The drilling velocity under realistic conditions is an important parameter for the evaluation of the applicability and competitiveness of the spallation technology. The model is based on transient head conduction due to a moving convective point surface and on a specific temperature which is required to initiate thermal crack formation. According to the model, the drilling velocity increases with a logarithmic shape until it reaches the melting temperature limit. If the surface partially melts, the drilling process will be significantly impeded. A validation showed good agreement between experimental data gained at our laboratory and the proposed model. The presented model can also be used to design and evaluate thermal drill heads with respect to the adjusted flame temperature and jet velocity. The evaluation showed that by using the spallation technology interesting ROP of about 6-7m/h can be reached already at moderate operating conditions. As a last step the drilling velocity was expanded to integrate an estimation of the costs involved in the drilling process.

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