Design of a hydrothermal spallation drilling tool – Flame impingement experiments

Panagiotis Stathopoulos, Thierry Meier, Tobias Rothenfluh, Martin Schuler, Dragana Brkic, Philipp Rudolf von Rohr

[1] ETH Zurich, IPE-MAVT, Sonneggstrasse 3, 8092 Zurich, Switzerland

pstathop@ethz.ch

Keywords: Hydrothermal spallation drilling, Drilling tools, Hydrothermal flame impingement.

ABSTRACT

Despite the great potential of geothermal electricity production, its exploitation is hindered from the high investment risk of geothermal projects. Exploration, test and production drilling account for 40-70% of the costs for a geothermal power plant. Half of this amount is invested without knowing whether an energy source will be found, or if it will be productive in an economically viable way. These facts call for a reduction of the drilling costs, in order to make geothermal electricity production competitive.

Spallation drilling is a technology that could achieve this goal. It takes advantage of the properties of crystalline rocks, to break them into small disk-like fragments (spalls) due to thermal stresses. For the deeper boreholes of geothermal power plants and Enhanced Geothermal Systems (EGS), flames in supercritical water (hydrothermal flames) should be implemented to heat up the rock and induce these thermal stresses.

This paper presents the first steps towards the development of a hydrothermal spallation drilling tool in a novel high pressure pilot plant. The drilling nozzles are characterized based on their heat transfer capabilities, by measuring the two-dimensional impingement temperature profiles of the flames that are produced from each nozzle. The optimized design of the drilling tool has been successfully implemented in drilling experiments on Iragna granite rocks.

1. INTRODUCTION

Spallation drilling applies the impingement of flames on rocks, in order to break them in small disk-like fragments (spalls), due to the induced thermal stresses (Rauenzahn 1989). The absence of any contact between the drilling bit and the rock and the demonstrated higher penetration rates in crystalline rock (J.A.Browning et al. 1965), could drastically reduce the costs for drilling.

The deeper boreholes of geothermal power plants and Enhanced Geothermal Systems (EGS) need a water-based drilling fluid for their stability (Augustine 2009) and for the transport of the cuttings to the surface. Hence, spallation drilling could be realized in these boreholes only with the use of flames in supercritical water (hydrothermal flames).

In order to investigate spallation drilling with hydrothermal flames, a novel high pressure pilot plant with an installed thermal capacity of 120 kW (which is several times higher than comparable facilities) has been built and commissioned. The plant operates at pressures up to 350 bar and it is able to accommodate rock samples with diameters up to 9.5 cm.

Transferring spallation drilling to high pressure aqueous environments introduces several new challenges that have yet to be addressed. One of the most important among them is the control of water entrainment in the hot hydrothermal flame-jets. Being able to control this physical process would mean that the impingement heat transfer conditions could be tuned for the needs of the drilling technology.

To address the entrainment issue, the heat transfer capabilities of seven different configurations of a hydrothermal flame-injection nozzle have been analyzed through the measurement of their impingement temperature profiles. The resulting insights in the impingement of hydrothermal flames supported the optimization of the initial drilling tool design.

2. EXPERIMENTAL SETUP?

2.1 Hydrothermal spallation drilling pilot plant

The experiments were conducted in the new hydrothermal spallation drilling plant of our lab. The plant is using water-ethanol mixtures of various compositions as a fuel and pure gaseous oxygen as an oxidation medium. The fuel and oxygen can be heated up to 420°C and 400°C respectively before their injection in the pressure vessel of the plant. Two high pressure plunger pumps provide the cooling water for the plant, a metering membrane pump is controlling the flow of its fuel mixture, while an air driven gas booster is used to compress the oxygen.

The core of the plant is its high pressure vessel, which has a volume of 5.8 lt, and it can withstand pressures of 600 bar at wall temperatures of 500 °C. Its inner diameter is 14 cm and the length of its inner space is 40cm. Furthermore, two individual positioning devices, similar to the ones presented by Prikopsky (Prikopsky 2007), are used to position sensors and rock samples in the vessel, while it is under pressure.

2.2 Combustion chamber and drilling nozzles design

Fig.1 presents the simplest design of the combustion chamber of the plant.

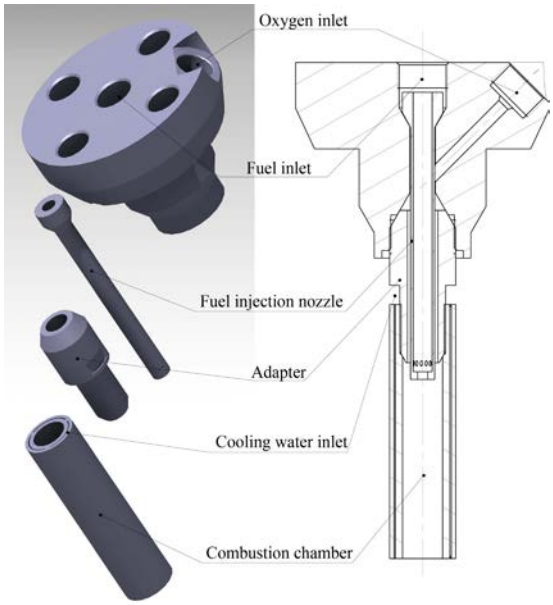


Figure 1 Combustion chamber of the hydrothermal spallation drilling pilot plant.

The heated fuel mixture is fed axially through a specially designed burner nozzle. Oxygen is fed from a radial hole and it flows through the annulus between the burner nozzle and the adapter. The mixing of fuel and oxygen takes place in the combustion chamber, and the resulting mixture is ignited by a heated wire.

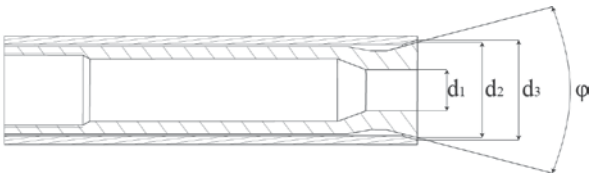


Figure 2 Combustion chamber outlet nozzle, with its parameters that are relevant for the design of the drilling tool.

The design of the drilling tool concentrates on the geometrical characteristics of the outlet nozzle of the combustion chamber. The parametric drawing of this nozzle can be seen in Fig.2, where the geometrical parameters relevant with the entrainment process are outlined. The nozzle produces a central jet, which is the actual flame-jet, and an annular jet that is produced from the cooling water of the combustion chamber. The injection velocity of each jet and their relevant angles have a direct influence on water entrainment in the flame-jet and consequently on its heat transfer capabilities (Ricou and Spalding 1961).

Seven different nozzles have been built and the values of their geometrical parameters are presented in Table 1.

Table 1 Nozzle geometrical parameters that were investigated during the impingement experiments.

Nozzle Nr.	d_1 (mm)	φ (°)
1	10	30
2	5	20
3	7.5	30
4	7.5	60
5	7.5	90
6	10	90
7	7.5	120

2.3 Impingement plate design

The efficiency of each nozzle as a heat transfer tool was analysed by measuring the two-dimensional impingement temperature profile of the flames-jets that the nozzle produced. These measurements were performed with a flat stainless steel plate, in which a matrix of ten thermocouples was welded. The exact positions of the thermocouples and the distance from each other can be seen in Fig.3.

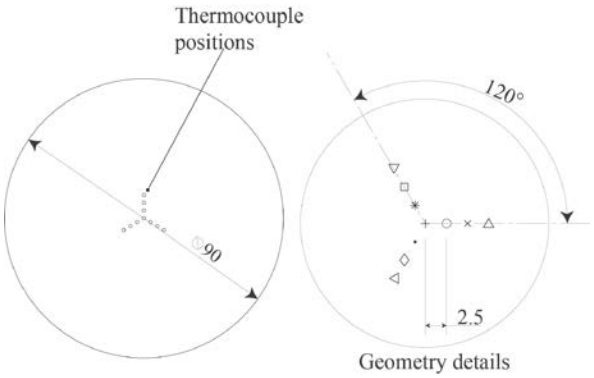


Figure 3 Thermocouple matrix, used for the measurement of the two-dimensional flame impingement profiles.

The temperature measurements covered a surface area that was relevant for the intended drilling technology. During spallation drilling, the heated part of a mechanically unconfined rock probe has to be thermally confined, in order to achieve the desired thermal stresses in the rock mass. The rock that surrounds the heated region must be at a much lower temperature, to avoid its expansion and the subsequent

relief of the induced compressive stresses. Rauenzahn (Rauenzahn 1989) and Wilkinson (Wilkinson 1989) based on the findings of Preston and White (Preston und White 1934) stated, as a rule of thumb, that the directly heated surface must be below 10% of the total surface of the rock sample. Given that the pressure vessel of the plant can accommodate rock samples with a diameter of 9.5 cm, the measurement area had an equivalent diameter of 15mm. Furthermore, the thermocouples were positioned at a distance of 2.5mm from each other.

2.4 Experimental plan

The effects of six parameters on the impingement temperatures were analysed during the experimental investigation. These parameters concern either the geometry of the problem or the plant operation. The present paper focusses on the influence of two geometrical parameters, the stand-off distance (SOD) and the water curtain angle and an operational one, the combustion chamber load.

The combustion chamber load is defined as the consumed fuel power divided by the chamber volume and it is a function of the fuel flow rate and its ethanol concentration. In the present work, it was changed by varying only the fuel flow rate and therefore only the flame-jet exit velocity was affected by it and not its outlet temperature.

The detailed measurement points for nozzles 1-5 and 7 are presented in Table 2.

Table 2 Operational conditions of the plant during the experiments with nozzles 1-5 and 7. the data for nozzle 6 are presented in the caption of Fig.7.

C_f	m_{cool}	SOD	m_f	m_{O2}
[%wt.EtOH]	[kg/h]	[mm]	[kg/h]	[NL/min]
20	350	15 20 25 30 40	20	119
			30	177
			40	236

Three values of the combustion chamber load have been implemented, while for each flame five SOD values were measured. The values presented here are the average of the 120 values that resulted during the 120 seconds of each measurement.

3. EXPERIMENTAL RESULTS – FLAME IMPINGEMENT PROFILES

The impact of the SOD on the impingement temperatures for two chamber loads is presented in Figures 4 and 5. Both figures show that the water entrainment led to fully mixed jets for SOD values between 25-40. All the thermocouples of the plate measured the same temperature, which was proportional to the chamber load. By lower values of the SOD (that is 15-20mm away from the chamber nozzle) higher temperatures were observed around certain thermocouples.

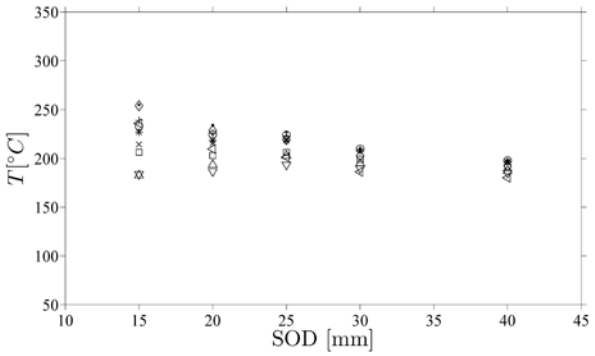


Figure 4 Impingement temperatures as a function of the SOD for a jet produced from nozzle 5 with m_f=20kg/h.

Fig.5 presents an experiment where the high-energy central jet raised the temperatures on the plate up to 345°C. At the same time, the thermal content of the flame-jet in Fig.4 was strong enough to produce temperatures of around 260 °C on the plate, which ?concentrated only to ?several thermocouples.

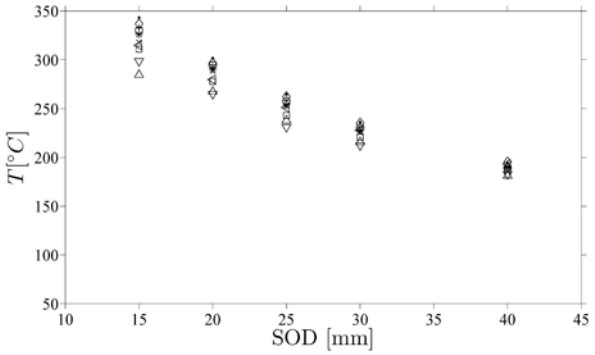


Figure 5 Impingement temperatures as a function of the SOD for a jet produced from nozzle 5 with m_f=40kg/h.

The direct impact of the water curtain angle on the entrainment intensity was another aspect that was investigated through a separate series of experiments. Fig.6 and Fig.7 present the temperature profiles of nozzles 1 and 6 respectively, as a function of the SOD. The larger water curtain angle of nozzle 6 directed the water away from the flame-jet and lowered the intensity of the entrainment phenomena. Higher impingement temperatures were measured and the increase of the jet velocity led to values as high as 420°C.

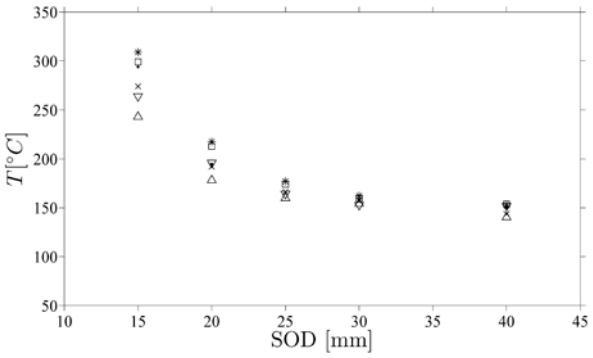


Figure 6 Impingement temperatures as a function of the SOD for a jet produced from nozzle 1 with m_f=40kg/h.

The measurements with nozzle 6 were carried out with a high combustion chamber load, reaching 78kW, while the load of the experiments with nozzle 1 (Fig.6) was 60kW. Nevertheless, the difference between the two profiles is large, especially at SOD between 15 and 20mm.

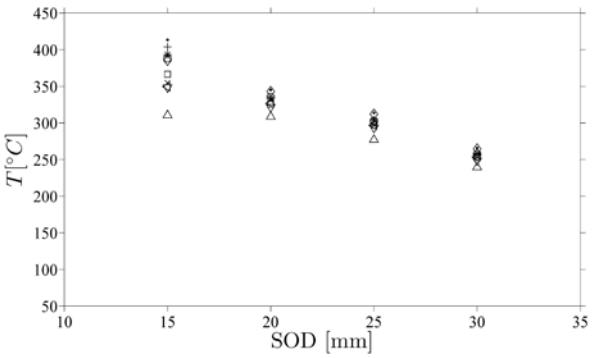


Figure 7 Impingement temperatures as a function of the SOD for a jet produced from nozzle 6 with m_f=60kg/h, C_f=17.5%wt and m_{o2}=310 NL/min.

4. INITIAL DRILLING EXPERIMENTS

After assessing the impingement results of Fig.7, and especially the temperatures for an SOD=15mm, we proceeded with the first drilling experiments, which were conducted with Iragna granite samples with a diameter of 83mm. The rock samples after the three experiments are presented in Fig.8.



Figure 8 Rock samples after the first three drilling experiments. The exposure time is from left to right 1, 10, 30 minutes and the small cavities are visible on the two samples on the right side.

All the experiments demonstrated a successful spallation of the rock samples and the produced spalls were in the form of sand-like particles. As a matter of fact, the enlargement of the cavity between experiments 1 and 2 has shown that the process was continuous. However, its slower enlargement between experiments 2 and 3 indicated that spallation has stopped after a certain time (between 10-30 minutes), most probably due to a heating-up of the rock probe.

The initial drilling experiments demonstrated the feasibility of spallation drilling with hydrothermal flames. It will be the goal of a next research project to optimize the design of the combustion chambers in order to achieve higher penetration depths and rates. Even these preliminary experiments have clearly proven that the temperature and heat flux values provided by free hydrothermal flame-jets can induce spallation in granite samples.

BIBLIOGRAPHY

Augustine, C. R. "Hydrothermal Spallation Drilling and Advanced Energy Conversion Technologies for Engineered Geothermal Systems." Ph.D. dissertation, Massachusetts Institute of Technology, 2009.

J.A.Browning, W.B. Horton, H.E.Fletcher, and H.L.Hartman. "Recent advances in flame jet working of minerals." *Seventh symposium on rock mechanics, Pensylvania state university.* 1965.

Preston, F. W., and H. E. White. "Observations on spalling." *Journal of the American Ceramic Society* (Blackwell Publishing Ltd) 17, no. 1-12 (1934): 137-144.

Prikopsky, K. "Characterization of continuous diffusion flames in supercritical water." Ph.D. dissertation, ETH Zurich, 2007.

Rauenzahn, R. M. "Rock Failure Mechanisms of flame Jet Thermal Spallation Drilling-Theory and experimental testing." *Int.J.Rock Mech.Sci* 26, no. 5 (1989): 381-399.

Ricou, F. P., and D. B. Spalding. "Measurements of entrainment by axisymmetrical turbulent jets." *Journal of Fluid Mechanics* 11 (1961): 21-32.

Wilkinson, M. "Computational modeling of the gas phase transport phenomena and experimental investigation of surface temperatures during flame jet thermal spallation drilling." Ph.D. dissertation, Massachusetts Institute of technology, 1989.