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Experimental Study of Hydrothermal Spallation Drilling

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Abstract. Geothermal energy has gained more and more attention from all around the globe for its cleanness and efficiency. In the meantime, wells are drilling more and more deeper to develop oil and gas resources. Low rate of penetration is the common problem faced by geothermal wells and deep oil wells. To speed up the development of geothermal energy and petroleum resources in deep formation, a hydrothermal drilling method is proposed here in this paper and the drilling mechanism along with an in-lab experimental setup have been analyzed.

1. Introduction

Conventional drilling method uses mechanical drill bits to crush and mill the rock. As the formation depth increases, both the rock strength and hardness are also increased which in turn cause the low rate of penetration. There is little progress right now in mechanical engineering method to deal with low drilling rate.

For some specific rocks, when the heat fluxes on the order of $0.5\text{--}10\text{ MW/m}^2$ are applied, the rocks tend to fail and spalls will be generated and ejected away from the hotspot [1-2]. The spallation process has been used for decades in the mining industry for drilling shallow blast holes using supersonic flame jets. As the well depth increases, the transport of spalls or cuttings will be difficult, sometimes impossible. In conventional drilling method, drilling fluids are used to transport cuttings away from the bit surface, into the annulus and finally to the surface for further disposal. Combining the thermal spallation method with conventional cutting transport method we then have the hydrothermal spallation method.

The previous hydrothermal spallation drilling experimental studies are specifically reviewed here to assess the technologies and techniques used to produce and characterize hydrothermal flames and optimization of the technology.

2. Conditions in a Deep Borehole Environment

The downhole environment encountered in drilling deep boreholes ($>3\text{km}$) is much different than atmospheric conditions in shallow boreholes where thermal spallation drilling has been traditionally used. Deep boreholes usually employ a drilling fluid to aid in the drilling process. In conventional rotary drilling, the drilling mud can perform the following functions: 1) it cools and lubricates the drill bit, 2) it pushes cuttings away from the bit surface and transports them to the surface, and 3) it maintain borehole stability by generating hydrostatic pressure along the whole borehole. The hydrostatic pressure exerted by the mud column not only maintains the wellbore stability, but also deal with well control problems caused by the high formation pressure. Conversely, too high of a hydrostatic pressure can cause drilling fluid to seep into the formation, a serious condition known as lost circulation.

From the discussion above, it is clear that any deep thermal spallation drilling system will require a liquid drilling fluid with sufficient density to deal with well control problems and cutting



transportation. Conventional thermal spallation systems are not designed to operate under such conditions. While drilling a test hole in a granite formation in Conway, Browning noted that his open-hole spallation drilling system could tolerate some influx of fluids from the formation, but the rate of penetration slowed markedly when water bearing zones were encountered in the rock. The maximum depth reached during drilling was only 304.8 m. Wells deeper than 3,048 m will require the drilling equipment to operate in a fluid-filled hole. In addition to aqueous conditions, much higher pressures will be encountered.

3. The Need for Hydrothermal Flame Research

If jet flames are to be used in a deep borehole environment to generate the heat fluxes needed to induce thermal spallation, then the technology to make flames in a high pressure, high density environment is needed. Figure 1 shows that if the water-based drilling fluid is used, the bottom hole pressure will be above the critical pressure of water. Therefore, the ability to produce stable, hydrothermal flames in supercritical water will be needed.

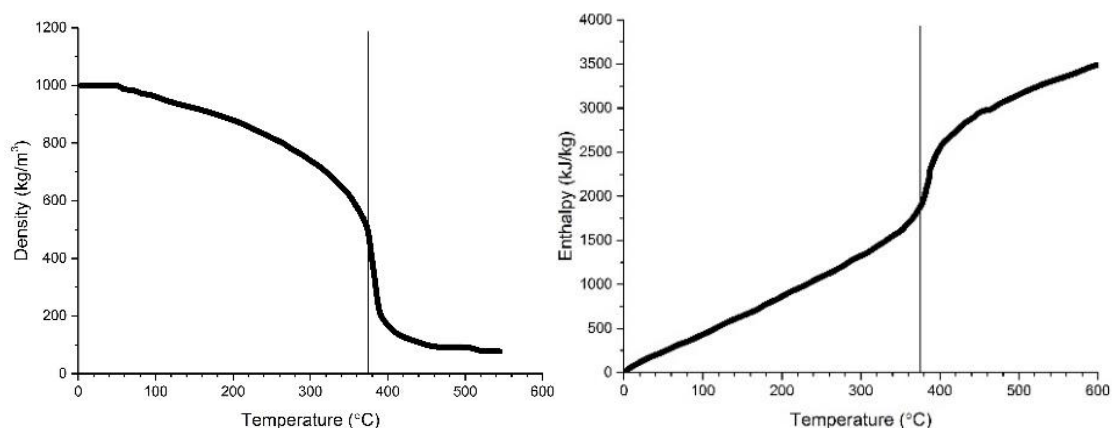
According to the definition, hydrothermal flame is produced in water over 22.1 Mpa and at 374 °C. At early stage, hydrothermal flame study focused on the high-temperature and high-pressure thermodynamic properties of a variety of water and gases' binary systems [3-5]. At conditions over the critical water pressure and temperature, light gases will mix with supercritical water to form homogeneous mixture. This kind of mixture can be ignited to provide the heat needed.

Even though they were first demonstrated in Franck's laboratory more than 2 decades ago, the research of hydrothermal flame remains preliminary. There's still much to do to conduct in-depth analysis of such a technology.

4. Properties of Supercritical Water Mixtures

The thermophysical and transport properties of water near and above 374 °C and 22.1 Mpa differ greatly from its properties at ambient conditions. At supercritical conditions, water has densities that are intermediate between liquid and gaseous water, the density and other properties can be tuned rapidly by changing its pressure or temperature. Figure 1 is an example of water properties at the pressure of 25 Mpa. The viscosity, dielectric strength, surface tension and other physical properties of the supercritical combustion environment can be greatly varied by adjusting the pressure, temperature, and composition of the system. For example, the viscosity at 400 °C is about one-tenth of that of liquid water at ambient temperatures, leading to higher diffusion coefficients.

Rather small changes in temperature or pressure near the critical point can cause dramatic changes in the solvation character of water-causing it to transition from a very polar, hydrogen bonding solvent at subcritical conditions that easily dissociates and dissolves ionic salts to a nonpolar solvent at supercritical conditions that solubilizes gases and light hydrocarbons and provides an attractive environment for treating heterogeneous wastes by oxidation.



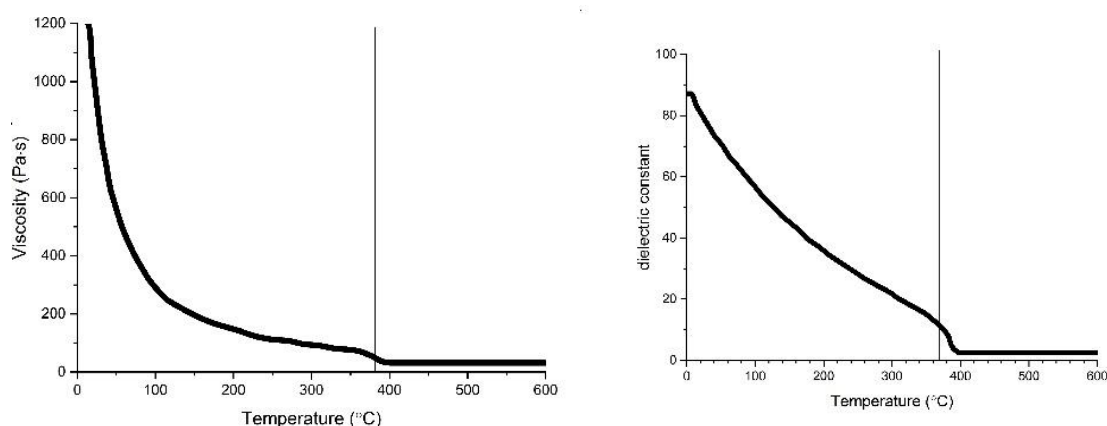


Figure 1. Water properties at $P = 25$ Mpa[6].

More specifically, at ambient condition, the dielectric constant of water at a pressure of 25 Mpa is 80. If you increase the temperature to 400 °C, the constant can decrease to less than 2. These effects, correlated with the decrease in water density, reduces water's hydrogen bonding power, making supercritical water behave like a non-polar solvent such as hexane. Above 375 °C, N_2 , O_2 , H_2 , CO_2 as well as benzene, ethane and methane are easy to be mixed with water completely. Under supercritical conditions, only a single phase exists, the interfacial mass transfer resistances among multiphase flow do not exist anymore. Ionic salt is very low in solubility in the supercritical water. It precipitates out of supercritical water mixtures quickly.

Supercritical water oxidation exploits the complete miscibility of O_2 and non-polar organic compounds in supercritical water to destroy toxic or non-biodegradable organic waste. It is a moderate temperature process that is usually carried out at temperatures between 450–650 °C and at supercritical pressures of 23 Mpa or higher. At these conditions, oxidation reactions take place in a homogenous, single-phase environment. To facilitate isothermal kinetic studies or to prevent thermal runaway in industrial applications, the concentration of reactive species is low. In order to achieve high reaction rates, much longer residence times are needed. A range of model compounds and waste streams, including municipal sludges and chemical and biological warfare agents have been studied [7].

Despite its attributes, supercritical water oxidation has two technical drawbacks: corrosion and plugging of the reactors and process equipment due to precipitating solids. Corrosion is caused by Cl^- and F^- often present in wastewater streams. These ions, combined with supercritical water and oxygen, can lead to severe corrosion under the condition of high pressure and temperature. To construct the equipment, nickel content alloys are preferred. Corrosion behavior in supercritical water oxidation systems has been well documented [8]. Equipment fouling and plugging is caused by the precipitation of salt particles in the wastewater as it transitions from the sub- to supercritical conditions [9].

Another disadvantage of supercritical water oxidation is the limited operating temperature and working pressure. Even using high-temperature nickel alloys, the temperature of the reactor wall under stress must usually be kept below 650 °C to 700 °C to avoid creep and failure. This limits the temperature at which the reaction can be carried out. Since the rate of the decomposition reactions follow Arrhenius temperature dependence, the reaction temperature must be kept quasi-isothermal to prevent thermal runaway. The lower kinetic rate results in much longer reaction times, requiring large reaction vessels to process a given volume of waste water [10].

5. Pressure Vessel and Combustion Chamber Design

A hydrothermal spallation drilling testing tool requires equipment which can withstand high pressures, safely operate hydrothermal flames and at the same time facilitate drilling operation. This section summarizes the designs of a combustion chamber and of a pressure vessel.

5.1. Pressure Vessel

The ship geometry includes its length and diameter as well as its technical and operational specifications (e.g., its materials, the largest operating pressure and temperature). Since the diameter of wells beyond 2500 m is on an average of 0.19-0.30 m, this sets the upper limit of the vessel diameter.

During the spallation drilling, to obtain the necessary thermal stress in rock mass, the thermal constraint of rock sample is required. The rock surrounding the hot zone must be at a lower temperature to avoid the release of thermal stress. Previous literature concluded that the surface heated directly should be less than 10% of the sample's overall surface. Therefore, a small size diameter rock sample can be used to easily achieve this requirement.

The specifications of the vessel designed by Panagiotis S [11] are listed in the following:

- Normal working pressure ranges from 25 and 40 Mpa. The maximum internal pressure is 65 Mpa for safety reasons.
- In the process of normal operation, the highest wall temperature reaches 500 °C.
- 2 windows in the main vessel body and 2 small windows on the upper flange create optical access.
- The vessel is 400 mm and 140 mm in inner length and the diameter, respectively.
- Silver coated stainless-steel rings having a rhomboidal cross section serve as sealings.
- The nickel alloy with high performance serves as the vessel material.

Additional related specifications of the pressure vessel include:

- Via the upper vessel part, the fuel stream is injected in the axial direction, with the highest temperature of 450 °C.
- The oxygen flow is fed radially through the same flange at the same maximum temperature as the fuel flow (450 °C).
- The cooling water stream (CW1) is injected radially in the radial direction at 20 °C.
- The water for the cooling mantle (CW2) is fed in the radial direction, on its upper side and flows downwards.

5.2. Combustion Chamber Design

The hydrothermal spallation drilling tool's combustion chamber should serve as a combustor while forming the flame jets to serve as tools for drilling.

Panagiotis S. proposed a new design of the combustion chamber (Figure 2) which has the following characteristics:

- Via a center hole in the fuel injection nozzle, an igniter is inserted in the chamber.
- In the similar angle as the oxygen flow, the fuel is injected. As a result, a recirculation area is created within the area with inserted igniter. In addition, this injection angle can minimize the impact of the fuel injection on combustion chamber wall.
- The combustion chamber must have a sufficiently large size to accommodate the higher heat load of combustion.
- The nozzle of fuel injection and combustion chamber must be easily adapted.

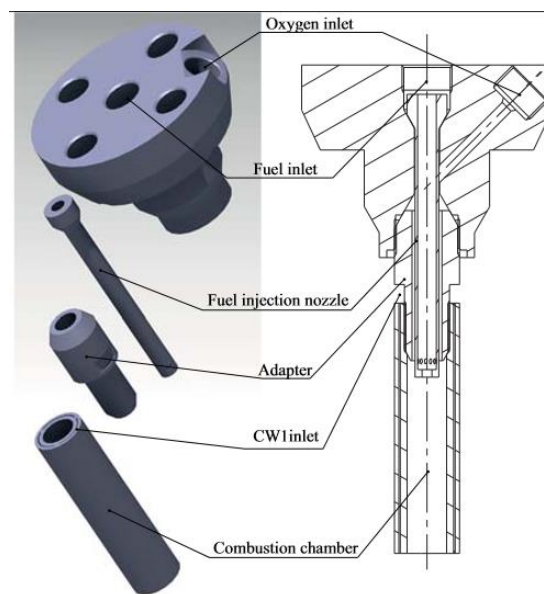


Figure 2. Combustion chamber in the high pressure vessel [11]

6. Ignition Experiments

For a smooth and reliable underground working condition, there must be a way to ignite the flammable hydrothermal mixture. Under the condition of spontaneous combustion, a typical borehole cannot be achieved at a reactant temperature below 100 to 250 °C. In the meantime, Subsurface heating of the reactants is hard to achieve since it is required for very high electricity. Therefore, forced ignition is still the only way to operate a hydrothermal flame within 2500 meters, and its study is essential for implementing spallation drilling technology. Since some metals are less likely to be oxidized by supercritical water than ceramics, a coiled wire was selected as an alternative to the ceramic igniter. The coil is composed of NiCr 60/15 and is temperature-dependent on its resistance and can withstand high temperatures. The wire thickness is 0.4 mm, while the outer diameter of the coil is 2.5 mm, with an inner diameter of nearly 1.7mm. At 20 °C, its electrical resistance and total length are 7.5 Ω and 30 mm, respectively.

7. Heat Flux Sensors and Their Calibration

Drill equipment design highlights the formation of flame jet and the optimization of heat transfer by hydrothermal flame impact. The behavior of hydrothermal flame as a free jet in liquid water differs from the conventional flame's employed by Rauenzahn and Wilkinson [12-16]. The condition near the hydrothermal flame has a great demand on the heat flow sensor especially on the chemical compatibility and temperature robustness. The temperature for maximum operating of the sensor regulates the point the most approaching to the flame that can be measured for heat flow. In the meantime, Rauenzahn reported that during spallation the most obvious temperature rising on the rock surface is nearly 500 °C. Since these sensors are higher than the surface of the peeling rock in thermal conductivity and are able to be cooled further, their maximum temperature for design is established at 700 °C. Likewise, in hydrothermal spallation drilling, heat flux values between 2000 kW/m² and 500 kW/m² are expected. Accordingly, the sensor design shall ensure that the maximum expected heat flow does not exceed its maximum operating temperature. Heat flow is a physical quantity that can only be measured indirectly. The simplest heat flux measurement follows temperature differences at two very close points within the material. Godefroy et al. constructed thin film sensors abiding by this principle. Similar sensors were presented from Holmberg and Diller [17] and Mabel and Huxtable [18], and each produces a voltage directly proportional to the incoming heat flow.

8. Design of nozzles

During the nozzle design water entrainment has to be controlled and this can be achieved by reducing the fluid density near the flame jet. Panagiotis S, et al [12] proposed a conceptual design of the nozzle. The cooling water is transferred from the flame jet through injection to an angle related to the combustion chamber axis. In addition, the outlet diameter of the central jet and circular jet controls the jet velocity and ratio.

Furthermore, the angle of water injection impacts the volume between impact plate and curtain, determining the amount of heat required to reduce the water density close to the flame. Energy required to reduce surrounding fluid's density will increase, and the efficiency will be lower with the increase of the volume. As a result, this volume will be reduced by a small curtain angle, whereas water inflow will increase because of the oblique impact. Such impact can accurately extinguish the flame at the point of impact. Clearly, a design balancing above two counteracting effects should be found.

9. Impingement Experiments

The water hot flame jet in liquid water bath has a strong characteristic of water. This phenomenon extinguishes the flame jet, affecting the efficiency of the technology. The thermal fluid split drilling rig should be able to control but not necessarily minimized the band rate. The dry crack drilling requires no more than the rock sample's brittle plastic transition temperature. The major strength of transcritical fluid is that it has a high convective heat transfer coefficient near its pseudo-critical point. Therefore, the combination of medium impact temperature and high heat transfer coefficient seems to be the best method to operate the drilling tools for hydrothermal spallation.

For the achievement of the above goals, expertise of three scientific disciplines is needed. First, the impact of water entrainment on flame impact and its limit should be analyzed. Second, underwater welding technology faces similar challenges. To protect the impact area of the gas jet and to provide an appropriate environment for the welding process, the water curtain is employed. However, the impact of the water curtain will still cause flow into the stagnation point of the flame. Therefore, the study of the oblique impact of underwater water jet can help reduce the flow in this direction, which is necessary for the design of drilling tools. Three scientific components of the drilling tool design process is shown in Figure 3.

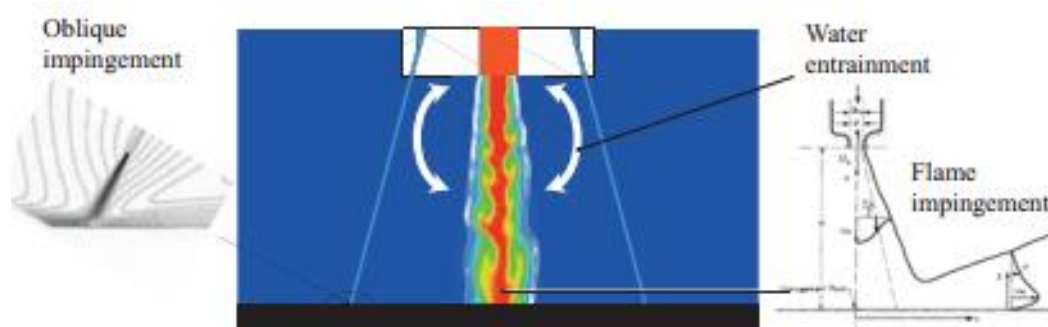


Figure 3. Hydrothermal flame jet in a water bath [11]

10. Conclusions

To recover geothermal energy and develop oil and gas resources in deep formation, hydrothermal spallation drilling method is proposed in this paper. A review work has been done on the following parts: the borehole condition, the mechanism of hydrothermal spallation drilling method, the equipment setups and the hydrothermal flame jet in a water bath.

Acknowledgement

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