J. of Supercritical Fluids 89 (2014) 48–57

Contents lists available at ScienceDirect

The Journal of Supercritical Fluids

journal homepage: www.elsevier.com/locate/supflu

Hydrothermal flame impingement experiments. Combustion chamber design and impingement temperature profiles

P. Stathopoulos, T. Meier, Ph. Rudolf von Rohr*

Institute of Process Engineering, Swiss Federal Institute of Technology (ETH), CH-8092 Zurich, Switzerland

ARTICLE INFO

Article history:
Received 11 July 2013
Received in revised form 26 November 2013
Accepted 1 December 2013
Available online 10 February 2014

Keywords:
Hydrothermal flames
Flame impingement
Water entrainment
Underwater welding
High temperature
High pressure
Spallation drilling

ABSTRACT

The current work presents the hydrothermal flame impingement experiments conducted for the design of a hydrothermal spallation drilling nozzle. The products of hydrothermal flames of mixtures of ethanol, water and oxygen were injected as free jets in a high pressure water bath. The nozzle design was based on ideas stemming from underwater welding and cutting of metal sheets. Water entrainment in the flame-jets and the heat transfer capabilities of flames injected from various nozzles have been analyzed by measuring their impingement temperature profiles on a flat stainless steel plate. It was found that the thermal-to-kinetic energy ratio of the jet has a direct influence on the entrainment of water in it. Furthermore, the cooling water of the combustion chamber was injected in various angles to the axis of the jet resulting to different entrainment rates. It was found that higher water injection angles reduced the rate of entrainment. Finally, it was indicated that at certain operational points of the jet, its trans-critical properties had an important influence on the impingement temperatures.

1. Introduction

A way to make geothermal electricity supply financially more profitable is to considerably reduce the drilling costs for the construction of geothermal wells [1]. Spallation drilling applies the impingement of flames on rocks to break them in small disk-like fragments (spalls), due to the thermal stresses induced in them [2]. The absence of any contact between the flame nozzle and the rock and the higher penetration rates of the method in crystalline rock, drastically reduce the costs for drilling [3]. Especially for the deeper boreholes of geothermal power plants and Enhanced Geothermal Systems (EGS), spallation drilling would require flames in supercritical water (hydrothermal flames) injected as free jets in a high pressure aqueous environment. This method of injection and its heat transfer characteristics are dominated by the strong water entrainment that quenches the flame-jets and affects the efficiency of the technology. A hydrothermal spallation drilling tool should be able to control but not necessarily minimize the entrainment rates.

Spallation drilling requires high heat flux values but moderate surface temperatures that do not exceed the brittle-plastic transition temperature of the rock samples. The main advantage of trans-critical fluids is their very high convective heat transfer coefficients near their pseudo-critical point [4]. Hence, the combination of moderate impingement temperatures with high heat transfer coefficients seems to be the optimal way to operate a hydrothermal spallation drilling tool. Another very important aspect of spallation drilling is the degree of confinement of the heated region of the rock surface. It has been suggested [5] that the heated area of the rock must not be higher than 10% of its total surface, in order to ensure thermal confinement. If this surface area is higher, the produced thermal stresses would be relieved through the expansion of the rock, which will not spall. The experiments presented in the current work aim to identify the operational conditions of free hydrothermal flame-jets, which could possibly lead to thermal spallation of granitic rock.

2. Hydrothermal spallation drilling experimental facility

2.1. Plant infrastructure

The experiments were performed in the high pressure pilot plant of our research group. The plant uses water–ethanol mixtures as a fuel and gaseous oxygen as an oxidation agent and it has an installed combustion capacity of 120 kW at a maximum operating pressure of 350 bar. It consists of five units namely the fuel, the oxygen, the two cooling water lines and the effluent water tubing.

A three-way valve (3WV-1, in Fig. 1) mixes DI water and ethanol before the inlet of the fuel pump (FP-1), which compresses the mixture at pressures up to 350 bar. The density and the mass flow of

* Corresponding author. Tel.: +41 446322488.
E-mail addresses: philippr@ethz.ch, yelias@ipe.mavt.ethz.ch (Ph. Rudolf von Rohr).

0896-8446/$ – see front matter
http://dx.doi.org/10.1016/j.supflu.2013.12.005

DI	deIonized (water)
EGS	Enhanced Geothermal Systems
EtOH	ethanol
Fr	Froude number
Gr	Grashof number
P&I	process and instrumentation
Re	Reynolds number
SOD	stand-off distance

Latin letters

c_p	isobaric specific heat capacity, J kg^{-1} K^{-1}
d	diameter, m
E	energy, J
m_f	mass flow rate of the fuel stream, kg/h
p	pressure, bar
C_f	ethanol concentration of the fuel stream, wt.%
L	penetration length, m
M	momentum flux, N s m^{-2} s^{-1}
P	combustion chamber thermal power (only fuel), kW
T	temperature, °C
V_{jet}	jet velocity, m s^{-1}

Greek letters

θ	angle, °
λ	oxygen-to-fuel ratio, –
ρ	density, kg m^{-3}
ϕ	angle, °

Subscripts

av	average
b	for the entrainment parameter
cw	cooling water
dl	dimensionless
f	fluid
kin	kinetic
pc	pseudo-critical
th	thermal
0	injection conditions
∞	water conditions

the mixture are then measured (FMI-1) and their values are used to control its composition and flow rate respectively. The fuel is subsequently heated (HX-2) up to a maximum temperature of 420 °C before its injection in the combustion chamber of the plant.

An air-driven high pressure booster (OC-1) compresses oxygen from a 12-bottle bundle to a 300 bar reservoir, whereas a front pressure controller (PIC-1, in Fig. 1) defines the oxygen inlet pressure to the tubing of the plant. The mass flow rate of oxygen is controlled (FC-1) and it is electrically heated (HX-1) up to 400 °C prior to its injection to the combustion chamber of the plant.

Cooling water is supplied from two pumps (WP-1 and WP2), one of which (WP-1) provides water to the cooling mantle of the pressure vessel. The second pump delivers cooling water to the effluent stream of the vessel (CW3) and to the combustion chamber (CW1), the flow rate of the latter being measured and controlled (FC-2).

The cooling water leaving the cooling mantle is mixed with the combustion products, thus realizing their first cooling step, whereas a second step is realized by mixing the resulting stream with the CW3 steam. The temperature after this second mixing step is kept always below 80 °C to protect the pressure controller of the plant (RV-10) from cavitation phenomena.

Table 1
Accuracy of the plant measuring devices.

Device name	Device type	Measurement uncertainty
FC-1	Mass flow controller	±0.5% of the actual value
FMI-1, 2, 3	Coriolis mass flow meters	±0.15% of the actual value
FMI-1	Density measurement	±0.5 kg m^{-3}
RV-10	Pressure controller	±0.7% of the actual value

The accuracy of each measuring device and the accuracy of the pressure control are presented in Table 1.

2.2. High pressure vessel

The pressure vessel of the plant has a volume of 5.8 l, and its design pressure and temperature are 600 bar and 500 °C respectively. Its has an inner diameter of 14 cm and the length of its inner space is 40 cm. A stainless steel tube divides its volume in an outer cooling mantle and an inner space (Ø10 cm) where the hydrothermal flame is ignited. A drawing of the vessel with the implemented impingement plate is presented in Fig. 2.

The combustion chamber of the vessel comprises the fuel injection nozzle, an adapter and the combustion chamber nozzle. The fuel nozzle geometry defines the injection characteristics of the heated fuel stream in a parallel flow of oxygen. The oxygen stream flows in an annulus formed between the outer diameter of the fuel injection nozzle and the inner diameter of the adapter. The latter connects the upper flange of the pressure vessel with the combustion chamber nozzle. In the volume of this nozzle the reactants are mixed ignited and combusted and its outlet forms the flame jets, which are subsequently used to transfer heat to the rock sample.

3. Design of the combustion chamber nozzle

In the context of spallation drilling, the design of the combustion chamber outlet nozzles should achieve several goals that can be summed up as follows:

- Water entrainment in the flame-jet must be controlled.
- The impingement of the flames must produce temperatures of at least 400 °C at stand-off distances between 20 and 30 mm. These SOD values are chosen so that enough space is provided to allow the removal of the rock particles.
- The area of the plate affected from the flame impingement must be controlled, so that only a small part of it is rapidly heated-up.

In order to achieve these goals with the nozzle of our plant, knowledge was drawn from studies on water entrainment in direct steam condensation and underwater welding. Especially by underwater welding, a water curtain is used to protect the impingement region of gas jets and to provide a suitable environment for the welding procedure [6]. Yet, the impingement of this water curtain still causes a flow toward the stagnation point of the flame. Studies on the oblique impingement of submerged water jets can therefore help to control this effect. Fig. 3 summarizes the three scientific components of the nozzle design process.

Typically, flames are injected in air that has a lower temperature and a higher density. This density and momentum differences produce a turbulent shear layer between the jet and the surrounding air. The resulting turbulent mixing causes a flow of air into the jet, the momentum and temperature of which are gradually reduced. Ricou and Spalding [9] quantified the entrainment mass flow rate in a jet for the simple case of isothermal jets injected in a fluid with an arbitrary density. They directly measured the entrainment flow rate through a porous wall and developed a simple correlation for it (Eq. (1)). In Eq. (1), m_0 is the initial jet mass flow rate, ρ_0 and ρ_∞