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Heat transfer of supercritical mixtures of water, ethanol and nitrogen in a bluff body annular flow

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ABSTRACT

Hydrothermal spallation drilling is a promising drilling technique that could prove economically advantageous over rotary techniques for deep wells, where hydrothermal flames can provide the required heat to spall the rock. Assisted ignition of hydrothermal flames must be understood prior to the field implementation of the technology. The convective heat transfer in a burner setup has been therefore investigated, where the flow conditions are similar to those of a bluff body wake flow in annular geometry. Various ternary mixtures of water, ethanol and nitrogen were used as model working fluids to simulate the combustion conditions of water–ethanol mixtures with oxygen. Water ethanol mixtures were pre-heated between 350 °C and 420 °C, and nitrogen was pre-heated up to 400 °C, while the working pressure was set at 260 bar. The convective heat transfer coefficient from an electrically heated surface to the mixtures is presented.

1. Introduction

The hot surface ignition of a hydrothermal flame is a topic relevant to previous research projects [1], but has not been investigated so far. The mechanisms of hot surface ignition [2] indicate that ignition takes place locally at the points where the minimum heat transfer coefficient of the flow occurs. In order to implement existing models for the hot surface ignition, at least the values of the mean heat transfer coefficient from the heated surface to the flow have to be known, estimated or measured. The heating power of the igniter, its materials and the electrical connections are directly connected to the heat transfer characteristics of the flow in the given geometry and conditions. This motivated us to carry out the measurements of the heat transfer coefficient for a model mixture (water–ethanol–nitrogen), which will be the initial input for the ignition experiments and the respective model of a combustible mixture used in our lab (water–ethanol–oxygen).

The convective heat transfer coefficient of supercritical fluids has been the topic of numerous experimental investigations, a review of which can be found in the works of Pioro et al. [3,4]. In most cases experiments in simple tubular and annular geometries were performed with the focus on pure fluids mainly water and carbon dioxide. These investigations may be of use for nuclear engineering, but offer little help, once a combustible mixture flows over a heated surface in a diffusion flame combustion chamber. The geometry in this case leads to a flow similar to the one of a bluff body, to promote mixing of the reactants and thus it is not possible to use the correlations acquired from flows in tubular geometries.

Few publications can be found in the open literature on the heat transfer from mixtures, the work of Rogak [5], being the most relevant for the measurements of the present work. His measurements with mixtures of supercritical water (SCW) and oxygen have shown some interesting trends of the heat transfer coefficient and its corresponding maximum values. The shift of the bulk temperatures, where these maximum values were observed and the lower absolute values of the coefficients, attributed mainly to the lower c_p values of the resulting mixtures, were some of the most important findings of this work.

According to the works of Bazargan and Mohseni [6] and Hiroaki et al. [7], the position of the pseudo-critical point of a mixture in the thermal boundary layer of its flow is responsible for the behavior of its heat transfer coefficient. Although the pressure and temperature values of the pseudo-critical points are known for all the constituents of the ternary mixtures investigated, they are not available for the mixtures themselves. Only estimations of the expected values can be made based on the data of the critical points for water–ethanol and water–nitrogen mixtures presented form Abdurashidova et al. [8] and Japas and Franck [9] respectively. Purpose of the current work is firstly to investigate the heat transfer coefficient of a ternary mixture relevant for technical application in supercritical water, and secondly to give the necessary data for the design optimization of an ignition setup for hydrothermal flames. The aimed heat transfer coefficient measurements are crucial for the dimensioning of a hot wire igniter, its electrical power and its geometry.

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Nomenclature

Latin letters

A	Surface (m^2)
$b_0$andb_1	Regression parameters for the resistance-temperature function
d	Diameter (m)
V	Voltage (V)
m_f	Fuel mass flow (kg/h)
m_{N_2}	Nitrogen mass flow (Nl/min)
$\dot{q}$	Heat flux (W/m^2)
R	Electrical resistance (Ω)
T_∞	Fluid bulk temperature (°C)
T_w	Igniter surface temperature (°C)
$\dot{V}$	Volumetric flow rate (m^3/s)

Subscripts and abbreviations

AWG	American wire gauge
SCW	Supercritical water

2. Materials and methods

2.1. Measurement concept

The measurement of the convective heat transfer coefficient of a flow, is based on the relation shown in Eq. (1), defining the convective heat transfer coefficient. The exchanged heat flux between a heated surface and a fluid ($\dot{q}$), the bulk temperature (T_∞) of the fluid and the surface temperature (T_w), have to be known or measured.

$$\dot{q} = h(T_w - T_\infty) \tag{1}$$

Due to the difficulty of the measurements in a high pressure–high temperature environment and the lack of space in the high pressure setup in our lab, a simple experimental setup had to provide as much data as possible, with as less measuring parameters as possible. A K-type thermocouple with a 3 mm diameter was used for the bulk temperature measurement, while the heat flux was calculated from Eq. (2) based on the voltage and current values fed to the heated surface, and the surface value itself.

$$\dot{q} = \frac{VI}{A} \tag{2}$$

The challenging direct measurement of the surface temperature was resolved with the implementation of a ceramic igniter made of silicon nitride, which had a linear and favorable temperature dependence of its resistance. By calculating the resistance through measurement of the voltage and current values fed to the igniter, the average temperature of its heated length could be measured.

As a result, the available data for the heat transfer conditions could be acquired through the voltage and current measurements, supplemented from the measurements of a K-type thermocouple.

2.2. Heated surface characteristics – Igniter

The igniter used as a heated surface is a cylindrical body consisting primarily of hot pressed silicon nitride (HPSN). The electrical resistance is implemented in the body by a sintering procedure and it consists of approximately 80 vol.%. silicon nitride while the rest is additives, $MoSi_2$ and TaN. The outer surface of the igniter is electrically insulating, its total length is 90 mm, while its heated zone is 40 mm long and has a 4 mm diameter. The dependence of its resistance from its temperature was calibrated in a high temperature oven up to temperatures of 520 °C. The calibration of the igniter at higher temperatures was not possible because the material used for soldering its electrical contacts melted above 550 °C. Nevertheless, calibration data provided from the construction company [10] for a reference igniter show a linear dependency up to temperatures of 1000 °C. A calibration line is presented in Fig. 1, together with its confidence intervals, computed according to the the orthogonal regression method [11].

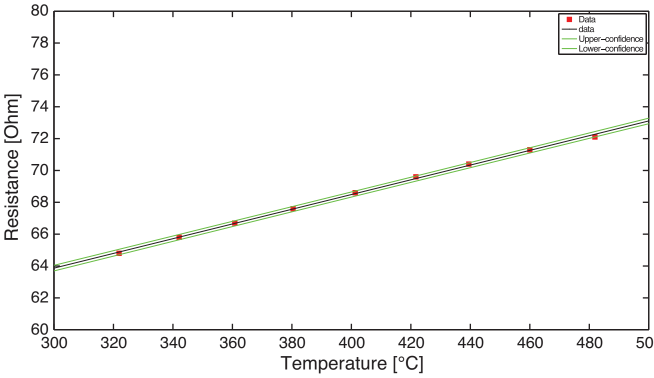

Fig. 1. Igniter calibration curve ($R = b_0 + b_1T_w$). Confidence interval ±0.5%.

The temperature in the calibration experiments was measured with two K-type thermocouples positioned near the igniter and its resistance was measured with a digital multi-meter. The accuracy of the thermocouple measurement was ±1.5 °C, and of the multi-meter 0.8% of the measured value. The error of the surface temperature measurement through the resistance measurement (inverse regression) was calculated from Eq. (A.2).

The resistance-temperature correlation defined from the calibration experiments gives the values of the temperature in the core of the igniter, which has a diameter approximately 3 mm. This value will not be the same with the surface temperature of the igniter, when it operates in a strongly convective environment. The thermal resistance of the electrically insulating layer of HSPN must be also taken into account in this case. In our experiments the thermal conductivity of this layer is estimated from the values reported in the work of Watari et al. [12] at the same temperature as the core. Accordingly, the value of the surface temperature of the igniter is corrected from simple 1-D conduction in a cylinder.

2.3. Experimental setup

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 oxygen as an oxidation medium and is capable of reaching fuel power of 120 kW. Fuel and oxygen can be preheated at temperatures 420 °C and 400 °C respectively prior to their injection in the pressure vessel of the plant. Two high pressure plunger pumps provide the cooling water, a membrane pump feeds the fuel and an air driven gas booster is used to compress the gas. Core of the plant is its high pressure vessel, where all experiments are carried out. It has a volume of approximately 5.8 l, and it is designed to 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 40 cm. Optical access to the vessel is provided by two small sapphire windows on its head. Probe access and positioning, while under pressure, is achieved with two individual positioning devices similar to the ones presented by Prikopsky [1], the positioning accuracy of which is 0.2 mm.

A drawing of the upper part of the vessel is presented in Fig. 2.

The inner space of the pressure vessel is divided by a stainless steel tube in the outer cooling mantle and the inner space where the hydrothermal flame will be ignited. Pressure balance between the two volumes is provided form 12 holes (diameter 1 mm) positioned at the bottom of the dividing steel tube. The diameter of