Thermo-Fluid Effects in Microwave Plasma Pyrolysis of Methane

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Abstract: A computational thermo-fluid flow model is used to study the effects of flow injection, flow rate, and methane concentration on microwave plasma pyrolysis of methane. Simulations of the operation of a microwave plasma torch with a mixture of argon and 1% or 10% methane in forward vortex flow mode show the confinement and advection of the power-deposition volume as well as its quenching with increasing methane concentration.

1. Introduction

The use of fossil fuels, such as methane, as a thermal energy source is a major contributor to carbon dioxide emissions. In contrast, the use of methane as a chemical feedstock, particularly to produce hydrogen and high-value carbon products, can reduce CO_2 emissions and help fulfil societal needs for energy and carbon-based materials. The use of microwave plasma for methane pyrolysis has distinct advantages such as high conversion rates, rapid response, and compact footprint of installations.

2. Methods

A thermo-fluid flow model is used to study the effects of flow injection, flow rate, and methane concentration on microwave plasma methane pyrolysis. Microwave energy absorbed by the plasma is described by a volumetric heat source spatially distributed following a Gaussian profile:

$$Q = \int_{\Omega} Q_0 \, exp\left(-\frac{r^n}{2\sigma_r^2} - \frac{z^n}{2\sigma_z^2}\right) dV, \qquad (1)$$

where $\sigma_r = 0.4R$, $\sigma_z = R/\sqrt{2}$, $R = 13$ mm is the radius of the discharge tube, r is the radial and z the axial coordinates, centered in the middle of the discharge tube – waveguide interaction region (Fig. 1a). The working gas is injected tangentially through 4 inlets. The model assumes laminar, steady-state conditions. The simulations describe flow dynamics and heat transfer in the reactor to understand flow behavior and power dissipation, and to estimate characteristic transport scales to complement experiments.

3. Results and Discussion

The simulations were conducted for the torch operating at atmospheric pressure, net microwave power $Q = 2$ kW, with a mixture of argon with 1% methane or 10% methane for 20 and 40 m/s average inflow velocity. Representative results (Fig. 1b) show streamlines surrounding the power deposition volume, causing it to stretch downstream.

Results of the temperature distribution through the discharge tube for different inflow velocities and methane concentration (Fig. 1c) show that the high-temperature region is more concentrated towards the central axis of the discharge tube for the 10% methane case compared to the 1% methane case. Increasing the flow rate further concentrates this region over the central axis and elongates the high-temperature region. This behavior is due to the presence of backflow towards the center of the tube.

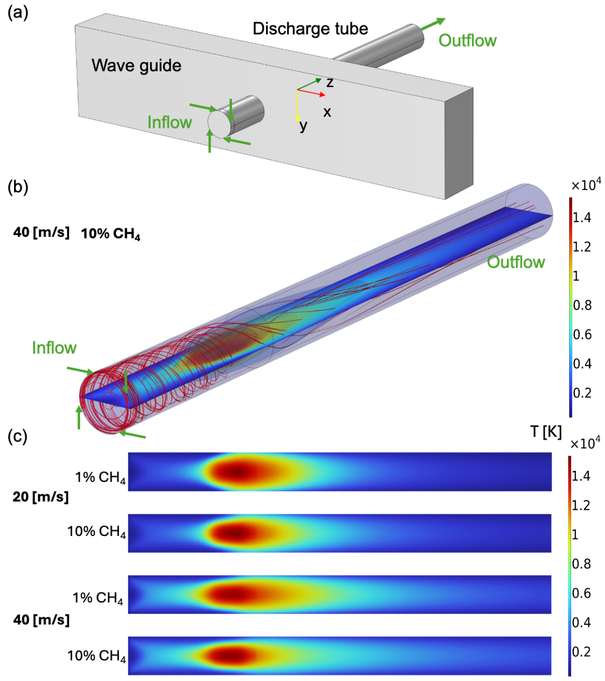

Fig. 1. Microwave plasma reactor model. (a) Geometry, (b) streamlines and temperature distribution, (c) effect of flow rate and methane concentration on temperature.

4. Conclusion

A thermo-fluid flow model of a microwave plasma reactor operating at atmospheric pressure with Ar-CH_4 as working gas shows higher methane concentrations increase the heating near the central axis, while increased flow rates elongate the high temperature region downstream.

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