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Effect of local rearrangements in the particle bed on the stability of filtration combustion of solid fuel

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ABSTRACT

The effect of local rearrangements in the particles bed during filtration combustion is studied experimentally and numerically. It is shown that for upward gas filtration and propagation of combustion front, there exists a stabilizing mechanism. It is due to filling of caverns formed as the result of burning-out of solid fuel by the fuel mixture from overlying layers. This mechanism prevents deformations and decay of the combustion front. The stabilization effect has a threshold for the gas flow rate that corresponds to the minimal fluidization gas velocity in combustion zone. In case of downward gas flow and combustion front propagation, this stabilizing mechanism does not occur.

1. Introduction

Nowadays gasification is considered as a promising way for the thermal conversion of solid fuels. The gasification in the mode of filtration combustion with counterflow of a solid fuel and a gaseous oxidant (in the reference frame related to the combustion front) results in a highly efficient heat recuperation [1,2]. In this case, the heat exchange between solid and gaseous flows and heat release during combustion can lead to a thermal "resonance" thus causing the temperature of the combustion front to exceed that of thermodynamic equilibrium for homogeneously mixed reactants [3–5]. This, in turn, facilitates the combustion of lean mixtures or low-caloric fuels, which is used in some industrial processes with high efficiency and lower cost [6].

For industrial gasifiers, their throughput is a key parameter. When operating in the mode of filtration combustion with solid and gas counterflows, the throughput is roughly proportional to the gas flow rate (in case of complete fuel conversion), since other gasification parameters, i.e., the combustion temperature and composition of gaseous products, are relatively insensitive to the gas flow rate. This weak dependence of gasification parameters on the gas flow rate is due to chemical processes being autolocalized within a relatively thin reaction zone where the temperature is high enough to provide sufficient rate of chemical reactions [4]. Thus, in the case when kinetic restrictions does not impose limitations, it is possible to raise the throughput, which obviously is desirable, just by increasing the gas flow rate. However, too high gas flow rate may disrupt the optimal gasification regime. There are several mechanisms for this disruption. For instance, when the gas flow rate grows, it eventually becomes so high that efficiency of the interphase heat exchange can become insufficient to recuperate the sensible heat from products to initial reagents. As a result, the heat balance might be broken and the process efficiency may fall dramatically. Another limitation for an increase in the gas flow rate relates to slow rates of heterophase reactions resulting in incomplete consumption of reagents. Moreover, a high gas flow rate brings in some technical problems, for example, entrainment of fine particles. It should be noted that luckily aforementioned restrictions occur beyond the region of usual gas flow rates which is ~0.1–0.5 m/s (normal cubic meters per second per square meter of the reactor cross-section).

At an increased gas flow rate, one should also consider the instability of flat combustion front due to thermo-hydrodynamic mechanism [7,8]. This instability occurs due to strong dependence of filtration resistance on the temperature that is common for any porous material but manifests itself especially for counterflow regimes with reaction trailing structure of filtration combustion.

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Nomenclature

a_s	thermal diffusivity of packed bed
d	particle diameter
G	gas flow rate
G_0	inlet gas flow rate
h	width of fuel bed
ΔP	pressure drop
q	reaction heat
T	temperature
T_*	characteristic temperature (the adiabatic combustion temperature
t_*	characteristic time of reaction at the temperature corresponding to stationary flat combustion wave
V_{cr}	critical velocity for the regime with compete fuel conversion
ζ_0	initial relative concentration of solid fuel
ξ_0	initial relative concentration of gaseous oxidant
ρ_s	density of solid particle
ΔT_*	adiabatic heating
Δt	time step of integration
i, j	indices for computational cells in x- and y-direction, respectively

Dimensionless parameters and variables

α	front inclination angle
γ	$\Delta T_*/q$
β	$\Delta T_*/T_*$
Γ_0	G_0/G_* inlet gas flow rate
δ	$\nu c_{p,g}\zeta_0/\xi_0 c_{p,s}$
H	h/x_* the width of fuel bed
η	solid fuel conversion
Θ	temperature
Ω	reaction rate

This instability mechanism usually causes local distortions that form an inclined front structure. Depending on specific conditions, the initially flat front can either transform into a new stationary S-shaped one or continue to incline further until the combustion surface splits into local burning spots [7,8]. These consequences are obviously undesirable in applications.

In many cases, the thermo-hydrodynamic instability emerges against the background of local movements of the friable bed material. These movements considerably change the evolution of the instability. Therefore, the objectives of the study were to investigate experimentally and theoretically the effect of mechanical rearrangements in the bed on characteristics of thermo-hydrodynamic instability and to determine constraints which this instability imposes on operating regimes of gasifiers.

2. Experimental setup

Experimental studies were performed using a 46-mm-i.d. quartz reactor filled with a mixture of 3–5 mm particles of charcoal and chamotte. Air was used as an oxidant. The gas flow rate varied within 0.11–0.4 m/s. Fig. 1 schematically presents the experimental unit. The experimental technique was described in detail in [9].

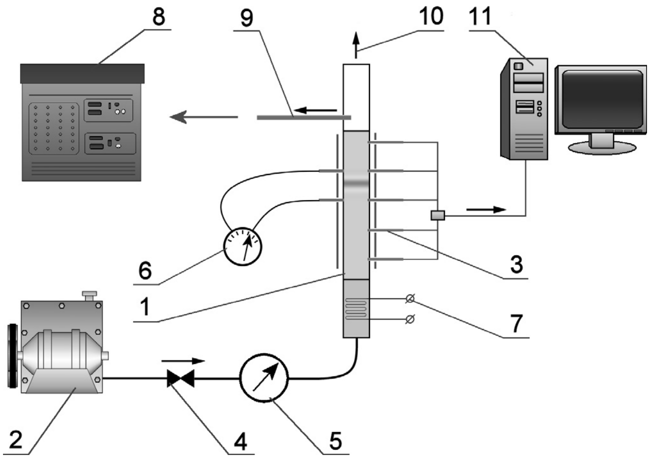

Fig. 1. Schematic of the experimental setup for filtration combustion. 1 – gasifier reactor; 2 – air compressor; 3 – thermocouples; 4 – valve; 5 – flowmeter, 6 – differential pressure gauge; 7 – electric heater (igniter); 8 – gas analyzer; 9 – probe for gas sampling; 10 – gas outflow; 11 – computer for data acquisition.

In the course of the experiments, we carried out visual observations, measured temperatures, and the pressure drop over a short section of the bed (approximately 50 mm in height) and sampled gaseous products.

3. Direction of the front propagation

We found out an interesting feature concerning front stability while experimenting with counterflow regimes of carbon/inert mixtures in the laboratory scale reactors. It turned out that the regimes with upward gas flow and the same direction of combustion front propagation were much more stable than the regimes with the same control parameters but with downward gas flow direction. This property of conterflow filtration combustion regimes is discussed below in more detail.

In cases when air was supplied from the bottom (as shown in Fig. 1), the combustion front propagated upwards (see Fig. 2a). Under certain conditions (specifically for the gas flow rate higher than 0.15 m/s) the combustion front deviated from the horizontal and became inclined, as shown in Fig. 2b. After this transformation, the new stable combustion front was nonplanar, S-shaped. This is in accord with theoretical predictions (see Section 4).

However, the inclination of combustion front did not affect dramatically the main characteristics of the combustion. For air gasification, when the fuel mixture consisted of 3–5 mm charcoal (10 wt%) and chamotte particles and at the gas flow rate in range 0.05–0.15 m/s, the producer gas mainly consisted of: N_2 – 63–68%, CO – 14–17%, CO_2 – 12–15%, H_2 – 2–3%. The influence of conditions on characteristics of filtrational combustion were discussed in our previous works, e.g. [9].

Similar effects of inclination instability were observed in studies of filtration combustion of gases [10] and was studied numerically [11].

The experiments with air supplied from the top and combustion front propagating downward showed a dramatically different combustion pattern. The combustion front lost its continuity just after initiation. It resulted in formation of a burnout zone (along one side of the reactor) that quickly reached the bottom (see Fig. 2c), and then was followed by a slow combustion of the remaining carbon. It was observed that the higher the initial fuel content, the more pronounced this instability was. Such a regime is shown in