Critical condition related to the activation of solid fuel particles; comparisons with experimental results for char combustion in a quiescent environment

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ABSTRACT

In order to verify appropriateness and/or usefulness of the critical condition related to the activation of solid fuel particles, being derived in the previous work, an attempt has been made for conducting comparisons by use of such experimental data in the literature as are reported to be burned in a quiescent environment. Use has been made of various carbonaceous solid fuels, from anthracite to low-rank coal char, as well as petroleum coke, after having confirmed kinetic parameters for the surface reaction that are indispensable for estimating combustion rate. Specifically, particle sizes examined in the present comparisons are those from 4 μm to 25 mm; ambient temperatures are those, higher than 1000 K. Use has also been made of the Arrhenius plot of the comprehensive parameter, consisting of frequency factor for the surface C–O_2 reaction, particle diameter, oxygen mass-fraction, and pressure ratio, upper half of which, separated by the critical condition, corresponds to that for particle burn-out with the surface reaction being activated. In general, a fair degree of agreement has been demonstrated in the present comparisons, as far as the trend and approximate magnitude are concerned, suggesting that the formulation used has captured the essential feature of the particle combustion, which has never been elucidated. Furthermore, it has been confirmed that the reduction in particle size does not necessarily favor the particle combustion and that the surface reaction ceases to be activated when the particle size is reduced below the critical one.

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1. Introduction

Because of the practical importance, relevant to coal/char utilization, aerospace applications with carbon–carbon composites, ablative carbon heat-shields, and/or propulsion with high-energy–density fuels, extensive research has been conducted for the carbon combustion not only experimentally but also theoretically/numerically, and accomplishment hitherto obtained is summarized in some of the comprehensive reviews [1–13]. Nevertheless, because of complexities involved, there still remain several problems indispensable for understanding basic nature of the combustion, with commanding fundamental interests.

As has been well-recognized, sizes of solid fuels in general can exert great influences on the particle combustion. While much of the understanding has been based on the d^2-law, so that there prevails the premise that the burn-out time reduces with decreasing particle size, it has been confirmed [10,12,14] in reality, by use of both experimental [15] and theoretical [16] results, that particles with excessively smaller sizes are unfavorable to the ignition, due to the fact that they have higher ignition temperatures and therefore then require higher ambient temperatures to achieve ignition, because of the heat loss, being increased as the particle size drops. As for the history of particle temperatures [16], characteristic of ambient temperatures and/or particle sizes, it has been reported [10,12,14] that there appears an initial, rapid temperature-rise, followed by a plateau stage with a slight temperature-rise, prior to the activation of particle combustion, as had been explained in the early textbook [5].

In this context, knowledge hitherto accumulated implies that there exist critical sizes for the particles to burn out. In order to verify this implication, an attempt [17] has been made to analytically obtain a critical condition, by use of the asymptotics, with focusing on the plateau stage. This attempt has successfully been

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Nomenclature

A	reduced surface Damköhler number	δ	product(CO_2)-to-carbon mass ratio
B	frequency factor	ε	emissivity
c	specific heat	θ	perturbed temperature
c_p	specific heat of gas at constant pressure	λ	thermal conductivity
D	diffusion coefficient	ν	stoichiometric coefficient
E	activation energy	ρ	density
m	mass consumption rate	σ_{SB}	Stefan–Boltzmann constant
$\dot{m}$	mass burning (or combustion) rate in dimensional form	τ	nondimensional time
q	heat of combustion		
r	particle radius	*Subscripts*	
T	temperature	C	carbon
Ta	activation temperature	O	oxygen or C–O_2 surface reaction
t	time	P	carbon dioxide or C–CO_2 surface reaction
W	molecular weight	s	surface
Y	mass fraction	∞	ambience
		0	reference
Greek symbols			
α	heat loss parameter	*Superscripts*	
β	conventional transfer number	$\sim$	nondimensional or stoichiometrically weighted

accomplished with identifying that the temporal variation of particle temperature can be determined by heat-release and -loss rates, just like that for the spontaneous ignition of the gaseous reactive mixtures, being studied in the 1930s [say, 18,19]. In addition, since a temperature-rise of the particle cannot be anticipated when the heat-loss rate is superior to the heat-release rate, we have succeeded in obtaining the critical particle size [17], below which surface reaction ceases to be activated, due to heat loss. It is also succeeded in obtaining a criterion [17] that can fairly correlate dominant parameters with the ambient temperature. A fair degree of agreement has further been demonstrated between experimental and theoretical results for graphite particles for which kinetic parameters are relatively well-known. Nonetheless, agreement with several data sources is absolutely insufficient to establish viability and/or validity of the criterion, so that further comparisons are to be required by use of experimental data from other reliable sources although we are to be faced to a problem that surface kinetics for those solid fuels are not necessarily known. That is, in elucidating such size effects as can appear in the particle combustion, it is a matter of great importance whether we can fairly estimate the combustion rate of those particles or not.

On one hand, combustion experiments with individual solid fuel particles have been conducted in an oxidizing gas environment that is in motion, relative to the particle. Some of their results [20–24] with graphite particles, necessarily set under the stagnation-flow configuration, have further been compared with theoretical results [24,25], in order to verify viability of the combustion rate, derived analytically with using basic characteristics of the chemically reacting boundary layers [26], because of its well-defined, one-dimensional nature, characterized by a single parameter, called the stagnation velocity-gradient [27]. Such experimental results as are obtained under low Reynolds numbers have further been compared with theoretical results [28,29] for a single carbon particle in a quiescent environment, after introducing some kinds of modifications for the mass transfer, aiming for expedient estimation of the combustion rate.

On the other hand, as for studies, relevant to utilization of pulverized coal combustion, experiments have been conducted extensively with solid fuel particles, less than about 100 μm in diameter, suspended in an oxidizer-flow that passes through a reactor [30–33]. Unfortunately, however, it has been rare for those results to be compared with theoretical results, in spite of the fact that such

formulations [34–38] for a spherical particle have widely been introduced in many textbooks. Furthermore, it has even been suggested that small particles may be considered to burn under quiescent condition [39].

The present study is intended to shed more light on the combustion of carbonaceous solid fuels, with putting an emphasis on its particle size. Here, special care is taken in elucidating existence of the critical size, above which particles can successfully be activated to burn-out, by use of experimental results reported in the literature, under recognition that fair estimation of the combustion rate by itself is absolutely indispensable for this verification. In addition, through conducting comparison with respect to the combustion rate, it is anticipate that appropriateness of the formulation for the particle combustion in the quiescent environment will be elucidated.

In the following, formulation relevant to the critical size derived previously [17] is first presented in Section 2, briefly, based on the fact that the plausible situation for small particles (<100 μm) can be that with negligible CO oxidation in the gas phase. Then, after having evaluated surface kinetic parameters, experimental comparisons with respect to the critical condition are conducted in Section 3, based on the analytical confirmation that the activation of particles can only be accomplished when the particle size, oxidizer concentration, ambient pressure, and temperature are, respectively, larger or higher than the individual critical values. Solid fuels examined are those, from anthracite to low-rank coal char, as well as petroleum coke, reported in the literature. A fair degree of agreement is demonstrated in the present comparisons, in general. Finally, concluding remarks are made in Section 4, with nomenclature tables, references cited, and appendices relevant to the combustion rate.

2. Formulation

2.1. Critical particle size

The problem of interest is the combustion of a spherical carbon particle (radius r_s and surface temperature T_s) in a quiescent environment (temperature T_∞, oxygen mass-fraction $Y_{O,\infty}$, and carbon dioxide mass-fraction $Y_{P,\infty}$). The major reactions considered are the surface C–O_2 and C–CO_2 reactions and the gas-phase CO–O_2