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An attempt for applying formulation of the carbon combustion in the stagnation flowfield to some experimental comparisons related to the boundary layer combustion

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A R T I C L E I N F O

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A B S T R A C T

An attempt has been made for conducting experimental comparisons by use of such experimental data in the literature as are seemed to have nothing to do with carbon combustion in the stagnation flowfield. Use has been made of aerothermochemical analyses reported in the literature, with the surface C–O_2 and C–CO_2 reactions and the gas-phase CO–O_2 reaction taken into account, with yielding explicit combustion-rate expressions for the combustion response in the limiting situations, by use of the transfer number in terms of the natural logarithmic term. Experiments chosen here are the carbon combustion in an impinging jet of oxidizer, that at the flat-faced cylinder in airflow, that in the natural convection, and that of a rotating disk. In spite of the experimental situation, seemed to be quite different from that in the stagnation flowfield, fair agreement has been demonstrated, in general, in experimental comparisons, because of appropriate evaluations for similarities that lie behind those. In addition, by virtue of this ascertainment, it has turned out that representative parts of those flow configurations can be specified uniquely by a single parameter, just like that in the stagnation flowfield, called the velocity gradient, with further allowing us fair estimations of the combustion rates at the representative positions in those flows. As for the fair agreement being demonstrated, it suggests that the formulation used here has captured the essential feature of the carbon combustion, even in those flows. Various contributions not only for qualitative/quantitative studies but also for practical applications are further anticipated, by use of the formulation used here, because of the single parameter that can specify the flow configuration.

1. Introduction

Carbon combustion has been a research subject, indispensable for practical utilization of coal/char combustion, aerospace applications with carbon–carbon composites (C/C-composites), ablative carbon heat-shields, and/or propulsion relevant to the high-energy–density fuels. Because of this practical importance, extensive research has been conducted not only experimentally but also theoretically/numerically, and accomplishment hitherto obtained is summarized in some of the comprehensive reviews [1–12]. Nevertheless, because of complexities involved, there still remain several problems indispensable for understanding basic nature of the combustion. Some of them also command fundamental interest, because of simultaneous existence of surface and gas-phase reactions, interacting each other.

The present study is intended to shed more light on the carbon combustion, with putting an emphasis on its combustion rate that can analytically be expressed by use of some of the basic characteristics of the chemically reacting boundary layers [13,14], under recognition that flow configurations are indispensable for proper evaluation of the combustion rate, especially in such a situation as would be influenced through an intimate coupling of the gas-phase reaction to the surface reactions in the overall combustion response. Here, focus is put on the stagnation-flow configuration that has frequently been used among various flow configurations, because of its well-defined, one-dimensional nature, characterized by a single parameter [15], called as the stagnation velocity gradient. It is even said that its introduction has facilitated mathematical analyses, experimental data acquisition, and/or physical interpretations.

Although experimental comparisons have been conducted not only for the carbon combustion in the two-dimensional stagnation flowfield [16,17], established over a cylinder, but also for that in the axisymmetric stagnation flowfield [18], over a sphere or a flat plate, agreement with several data sources is absolutely insufficient to establish validity of the theory and/or formulation. To this

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Nomenclature

A	reduced surface Damköhler number
a	velocity gradient in the stagnation flowfield
B	frequency factor
D	diameter
d	diameter of a flat-faced cylinder
E	activation energy
f	nondimensional stream function
Gr	Grashof number
g	gravitational acceleration
H	nondimensional ejection rate
h	heat transfer coefficient
j	$j = 1$ and 0 designate axisymmetric and two-dimensional flows, respectively
K	correction factor
L	separation distance between surface and jet nozzle
ℓ	regression length
$\dot{m}$	dimensional mass burning (or combustion) rate
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
T	temperature
Ta	activation temperature
t	time
U	flow velocity
v	velocity component along y
W	molecular weight
w	velocity component along the axis
Y	mass fraction

Greek symbols

β	conventional transfer number or coefficient of thermal expansion
δ	product(CO_2)-to-carbon mass ratio
κ	thermal diffusivity [$=\lambda/(\rho c_p)$].
λ	thermal conductivity
μ	viscosity
ν	stoichiometric coefficient or kinematic viscosity ($=\mu/\rho$)
ρ	density
ω	angular velocity

Subscripts

C	carbon
ig	appearance of CO flame over the burning surface
O	oxygen or C–O_2 surface reaction
P	carbon dioxide or C–CO_2 surface reaction
s	surface
∞	freestream or ambience

Superscripts

j	$j = 1$ and 0 designate axisymmetric and two-dimensional flows, respectively
$\sim$	nondimensional or stoichiometrically weighted

aim, the theory and/or formulation should be applied to further comparisons by use of experimental data from other reliable sources.

Experimental results chosen here are that of carbon combustion in an impinging jet of oxidizer, that at the flat-faced cylinder in airflow, that in natural convection, and that of a rotating disk, to be mentioned in detail later, none of which has ever been taken as an example for applying formulation of the carbon combustion in the stagnation flowfield. Note here that some of those data have even been used for determining kinetic parameters for sophisticated chemical schemes at the carbon surface, in spite of the fact that it has been rare to examine effects of flow configurations on the combustion rate in those results, from the viewpoint of aerodynamics. In this context, the present attempt can be considered for pursuing applicability of the present formulation on various carbon combustions in other flow configurations, through finding some kinds of similarities, lying behind. This attempt is further anticipated to facilitate fair estimation of the combustion rates at the representative positions, because representative parts in those flow configurations could be specified uniquely by the single parameter, just like that in the stagnation flowfield, called the velocity gradient.

In the following, formulation is briefly presented in Section 2, with taking account of the surface C–O_2 and C–CO_2 reactions and the gas-phase CO–O_2 reaction. Approximate, explicit combustion-rate expressions, for the three limiting situations are then presented. After that, experimental comparisons have been conducted in Section 3, by use of experimental data in the literature, in which flow configurations are clearly described. Concluding remarks are then made in Section 4, with nomenclature tables and references cited.

2. Formulation

The problem of interest considered is the carbon combustion (surface temperature T_s) in the stagnation flowfield (temperature T_∞, oxygen mass-fraction $Y_{O,\infty}$, and carbon dioxide mass-fraction $Y_{P,\infty}$), as shown in Fig. 1. The major reactions considered are the surface C–O_2 and C–CO_2 reactions and the gas-phase CO–O_2 reaction. The surface $C + O_2 \rightarrow CO_2$ reaction is excluded [19] because our primary concern is the combustion at high temperatures, say, higher than 1000 K. Crucial assumptions introduced are conventional, constant property assumptions with unity Lewis number, constant average molecular weight throughout the combustion field, constant value of the product of density ρ and viscosity μ, one-step overall irreversible gas-phase reaction, and first-order surface reactions. Surface characteristics, such as porosity and internal surface area, are grouped into the frequency factors for the surface reactions.

Since the solid usually possesses great inertia, because of the significant disparity between solid and gas, such properties at the surface as are the regression rate, species concentrations, and temperature, can change at rates much slower than those of the gas-phase transport processes. Therefore, under an assumption of quasi-steadiness in the gas phase, formulation has been conducted, as described in the previous works, so that only the final solution is presented herein, with adhering almost completely to the model

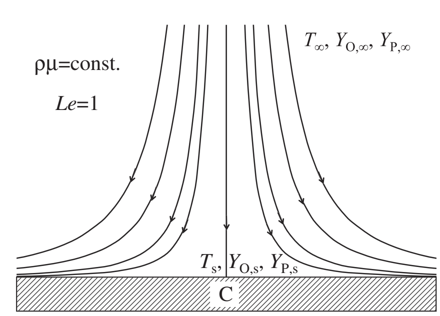

Fig. 1. Schematic drawing of the forward stagnation flowfield.