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On heat conduction between laser-heated nanoparticles and a surrounding gas

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Abstract

Uncertainties in modeling heat conduction in connection with the application of laser-induced incandescence (LII) to primary particle sizing are discussed. Comparing two models widely used in this context, namely those of Fuchs [(1963). On the stationary charge distribution on aerosol particles in a bipolar ionic atmosphere. Pure and Applied Geophysics 56, 185–193] and McCoy/Cha [(1974). Transport phenomena in the rarefied gas transition regime. Chemical Engineering Science 29, 381–388], it is demonstrated that arising differences may be accounted for by the choice of a proper "effective" thermal accommodation coefficient α_{eff}. In experiments on a large number of carbon blacks an overally good agreement between LII results and specified values for particle sizes based on electron-microscopy (EM) is obtained with a choice of $\alpha_{eff} = 0.25$ (based on the McCoy/Cha-model). As aggregate size is expected to influence heat transfer from primary particles, the experimental data are analyzed by a model for an effective heat transfer surface of fractal aggregates. Based on values for the average number of primary particles per aggregate as derived from photocentrifuge measurements the data yield an extrapolated value for the physical accommodation coefficient for isolated particles of $\alpha_1 = 0.43$.

Keywords: Nanoparticles; Heat transfer; Laser-induced incandescence; Primary particle sizing; Carbon blacks; Thermal accommodation coefficient

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1. Introduction

Carbonaceous nanoparticles in most practical instances emerge from the partial combustion of hydrocarbons. Apart from the most prominent visibility in daily life namely that soot particles in flames emit light with a typical yellow to reddish color and the enhancement of heat transfer in certain types of technical combustors (Hottel & Sarofim, 1967; Baukal, 2000) soot is mostly regarded as undesired side-effect and side-product of combustion processes. Current discussions on health hazards from soot and other nanoparticles (Maynard & Kuempel, 2005; WHO, 2005) underline the demand on the reduction of soot emission from technical systems, such as Diesel engines. On the other hand, industrial carbon blacks, particles purposefully produced on a scale of the order of 10 Mt/yr, are used in many kinds of industrial products, such as toners, pigments, tires, and self-regulating heaters. In order to obtain maximal performance from these products, carbon blacks have to fulfill several demands among which primary particle size is an extremely important feature.

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Nomenclature

c_p	specific heat at constant pressure
c_s	specific heat of carbon, see Eq. (5)
c_v	specific heat at constant volume
d_p	diameter of a primary particle
d_{med}	median diameter
$\bar{d}_p$	arithmetic mean diameter
D_a	diameter of an equivalent sphere
D_f	fractal dimension
$D(\lambda)$	spectral characteristic of detection system
E_i	laser irradiance
$E(\tilde{m})$	absorption function $E(\tilde{m}) = -\mathrm{Im}[(\tilde{m}^2 - 1)/(\tilde{m}^2 + 2)]$
f	Eucken factor
f_a	projected area prefactor
ΔH_v	heat of vaporization
k_a	thermal conductivity, see Eq. (8)
k_B	Boltzmann's constant
k_g	fractal prefactor
K_1, K_2	cumulants
m	particle mass
$\tilde{m}$	complex index of refraction
m_g	mass of a gas molecule
M_v	molecular weight of carbon vapor
M_λ^b	radiant exitance of a black body
N_p	number of primary particles per aggregate
p_0	gas pressure
p_s	vapor pressure over a particle
p_{s_0}	vapor pressure over a flat surface
$q(d_p)$	probability function of particle size distribution
Q	K_2/K_1^2, quality factor
$\dot{Q}_p$	heat transfer rate from an aggregate
Q_{abs}	absorption efficiency
$\dot{Q}_c$	heat transfer rate by heat conduction
$\dot{Q}_p$	heat transfer rate from a single primary particle
R	universal gas constant
R_g	radius of gyration
R_h	hydrodynamic radius
R_m	mobility radius
$S(t)$	LII signal of a particle ensemble
$S(t, d_p)$	LII signal of a single primary particle
$S(t, d_{med}, \sigma_g)$	LII signal of a lognormal particle ensemble
t	time
T	particle temperature
T_0	gas temperature
T_f	temperature of gas molecules emitted from particle surface
α	accommodation coefficient
α_1	physical accommodation coefficient
α_{eff}	effective accommodation coefficient
γ	c_p/c_v
ε_a	projected area exponent