Journal of Aerosol Science 102 (2016) 55–71

Contents lists available at ScienceDirect

Journal of Aerosol Science

journal homepage: www.elsevier.com/locate/jaerosci

Photophoresis on particles hotter/colder than the ambient gas for the entire range of pressures

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ARTICLE INFO

Article history:
Received 5 February 2016
Received in revised form
9 May 2016
Accepted 2 August 2016
Available online 31 August 2016

Keywords:
Photophoresis
Rarefied gas
Aerosols
Transition regime
Black body
Thermal radiation

ABSTRACT

Small, illuminated aerosol particles embedded in a gas experience a photophoretic force. Most approximations assume the mean particle surface temperature to be effectively the gas temperature. This might not always be the case. If the particle temperature or the thermal radiation field strongly differs from the gas temperature (optically thin gases), given approximations for the free molecule regime overestimate the photophoretic force by an order of magnitude on average and for individual configurations up to three magnitudes. We apply the radiative equilibrium condition from the previous paper (Paper 1) – where photophoresis in the free molecular flow regime was treated – to the slip flow regime. The slip-flow model accounts for thermal creep, frictional and thermal stress gas slippage and temperature jump at the gas–particle interface. In the limiting case for vanishing Knudsen numbers – the continuum limit – our derived formula has a mean error of only 4% compared to numerical values. Eventually, we propose an equation for photophoretic forces for all Knudsen numbers following the basic idea from Rohatschek by interpolating between the free molecular flow and the continuum limit.

1. Introduction

Illuminated particles suspended in a gas experience photophoretic forces (Loesche, Wurm, Teiser, Friedrich, & Bischoff, 2013; Rohatschek, 1995; Yalamov, Kutukov, & Shchukin, 1976a Yalamov, Kutukov, & Shchukin, 1976b). For directed illumination like in Fig. 1, a simple description for high Knudsen numbers is based on a kinetic description of the momentum transfer between impinging gas molecules and the particles, which is stronger on one particular side of the particles. Often this is related to a temperature gradient across the particles' surface which leads to a motion away from the radiation source.

Several experiments show photophoresis (Loesche et al., 2014; van Eymeren & Wurm, 2012; Wurm & Krauss, 2008) and the theoretical treatment of photophoretic forces in different pressure regimes has also progressed (Beresnev, Chernyak, & Fomyagin, 1993; Malai, Limanskaya, Shchukin, & Stukalov, 2012a; Reed, 1977; Yalamov et al., 1976a, 1976b).

The findings in the first paper (Loesche, Wurm, Jankowski, & Kuepper, 2016) (hereafter referred to as Paper 1) are based on the work by Hidy and Brock (1967), Tong (1973), and Yalamov et al. (1976b), which allow only low radiative fluxes I and small gas–particle temperature differences. It presented a new free molecular flow (*fm*) approximation, that now also supports the case of considerably higher radiative fluxes (I) and hotter/lower surface temperatures with respect to the surrounding gas (T_∞), while assuming the particle to be in equilibrium with an external radiation field at T_{rad}. It also

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http://dx.doi.org/10.1016/j.jaerosci.2016.08.013
0021-8502/

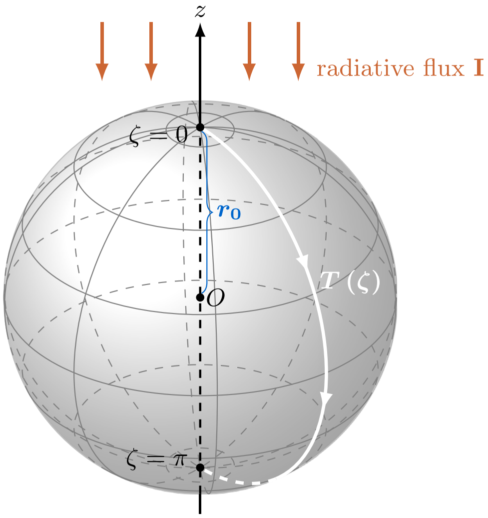

Fig. 1. Visualization of the situation considered. Illumination is directed along the z-axis, thus for a homogeneous particle the surface temperature only depends on ζ (spherical coordinate system (r, ζ, ξ)). The sphere's radius is r_0. The temperature of the gas is T_∞ ($r \to \infty$), the temperature of the radiation field is T_{rad}.

performs very well for particles of low thermal conductivity k which so far only Yalamov et al. (1976b) does, too. Paper 1 showed that the optimized linearizations used have an excellent effect on the results, reducing the minimum and the maximum relative error of the analytical equation (within the model) to $\approx -50\%$ and 7%, respectively.

Beresnev et al. (1993) and Chernyak and Beresnev (1993) proposed an advanced kinetic model for high Knudsen numbers, where also thermal radiation was considered. The external radiation field was at the temperature of the gas. For the *fm* limit they also provide a handy equation, that is similar to the one in Paper 1. However, the model only allowed small radiative fluxes I and therefore only small temperature difference between gas and particle.

Conversely, for low Knudsen numbers, especially in the slip-flow (*sf*) regime, there are hydrodynamic models proposed by Yalamov et al. (1976a), Reed (1977), and Mackowski (1989), where the first work also treats evaporation. None of these models allow high intensities I and also do not account for thermal radiation. For high intensities and temperature deviance of gas and particle, Malai et al. (2012a, 2012b) already proposed a model, incorporating thermal radiation and temperature dependent heat conductivities of gas $k_g(T)$ and particle $k(T)$ as well as gas viscosity $\eta(T)$. Like in Beresnev et al. (1993), the radiation field is at the temperature of the gas.

In this paper, we apply the findings from Paper 1 on other Knudsen regimes with the aim to find an accurate but handy interpolation function for the entire range of pressures. This interpolation also supports higher intensities, and therefore the mean particle surface temperature to differ from the gas temperature T_∞. Furthermore, it also includes the temperature of the radiation field T_{rad}, which is not necessarily the gas temperature, depending on the setting. The interpolation is based on approximations for the free molecular *fm* and continuum (*co*) limits following the findings of Hettner (1928) and Rohatschek (1995). However, as we have two temperatures, i.e. T_∞ and T_{rad}, which do not necessarily have to be the same, we propose another *sf* model in Section 3. From the equation for the *sf* regime we obtain the limiting case for vanishing Knudsen numbers (*co*). In the *sf* regime we account for thermal creep, frictional and thermal stress gas slippage and temperature jump at the gas–particle interface. We will not include temperature dependent k, k_g and η but show how to account for that in Section 5. For smaller particles the boundary conditions in the *sf* regime can also be extended by some additional addends which are linear in the Knudsen number (Malai et al., 2012a), introducing several more parameters. However, as mentioned before, we interpolate between the *co* and *fm* approximations. Therefore we do not incorporate too many Knudsen-number dependent boundary conditions into this model which vanish in the limiting case $Kn \to 0$ (*co*). A discussion of the results and a comparison to other models is done in Section 5.

All variables in this paper are also listed in Table A4, including some basic relations. Appendix A provides some additional information for the interested reader in the supplementaries.

2. Clarification/Knudsen regimes

The Knudsen number Kn is defined as the ratio of the mean free path of the gas molecules/atoms λ and the characteristic length of the problem r_0 (here this is the particle radius)

$$Kn = \frac{\lambda}{r_0}. \tag{1}$$