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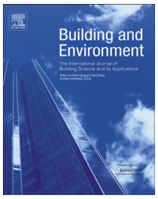

Numerical study of cooking particle coagulation by using an Eulerian model

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ABSTRACT

Airborne particles emitted in cooking process adversely affect human health and indoor air quality. In this work, we developed an Eulerian turbulence CFD model in combination with aerosol general dynamic equation (GDE) which is incorporated in a commercial CFD tool to investigate coagulation process of indoor particles. Experiments were conducted in a small scale chamber at different temperatures. In general, particles with a diameter range of 14–250 nm were measured and five different coagulation mechanisms including van der Waals, viscous forces and fractal effects were tested. The simulated results show good agreement with the experimental data. The coagulation coefficients with chamber temperatures of 22 °C, 42 °C, 62 °C and 82 °C were also calculated to elucidate the temperature effect on particle concentration. The validated model was applied to study water-boiling process in an environmental chamber. The temporal development of airflow temperatures and number concentrations of particles emitted by boiling water was investigated.

1. Introduction

Indoor airborne particles have been recently shown to cause a number of serious health problems such as reduced lung functions in many developed countries where people typically spend the majority of their time (80–90%) indoors and get exposed to various sources of airborne particles [19]. Indoor cooking is the main source in the generation of airborne particulate matter (PM) in non-smoking homes [23,41]. With the development of differential mobility analyzer (DMA) many studies have reported that cooking generated particles are majority in ultrafine regime [16,39,43]. Numerous studies have demonstrated the associations of airborne PM with negative effects on human health. These PM could be deposited in respiratory systems and thus could result in the respiratory diseases including lung cancer and cardiopulmonary deaths [3,32], especially for females frequently engaging in cooking [20]. The study carried by Ref. [36] has found that the PM inhalation also increases the long term risk of cardiovascular diseases. It has recently reported that airborne PM generated from cooking may have a significant impact on outdoor air quality in the urban environment [1]. Hence, an accurate prediction on the concentration of airborne particles emitted from cooking is urgently needed for assessing the health risk factors and environmental impact [30].

During the transport from cooking source to indoor spaces, the airborne particles may go through the growth, coagulation/aggregation, deposition and condensation. The size-resolved concentration profile of particle will be dictated by the intricate interplay between various physical processes as mentioned above. The spatial-temporal concentration of particles could be characterized by obtaining the solution of the aerosol general dynamic equation (GDE) which composes of a set of material or population balance equations over a control volume [6]. Several approximations for solving the GDE have been developed over the last few decades, such as moment method [13], "J-Space" method [38], sectional method [8] and moving finite element technique [40]. A comparison between these methods by Ref. [37] indicated that moment method was computationally ideal for modeling various situations involving Brownian coagulation and condensation.

The key aspect of moment method is to derive transport equations for the moments (some integral properties of the number density function) by integrating all the internal coordinates for the particles from the generalized population balance equation. The main advantage of the method is that the numbers of scalars required are very small, which makes the implementation in CFD by means of user-defined scalars/functions feasible. However, the

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Nomenclature

Notations

D	diffusion coefficient, m^2/s
D_f	fractal dimension
k	moment number
Kn	Knudsen number
(λ/r)	λ is the mean free path
L	internal coordinate, length in this paper, m
m_k	kth moment of density distribution, m^{k-3}
N	number of individual spherules or primary particles, v_i/v_1
N_0	initial number concentration $(/m^3)$
$N(t)$	number concentration at time t $(/m^3)$
$n(L)$	density of particle size distribution; one internal length coordinate, $1/m^4$
r_1	radius of individual spherule, m
r_i	particle of radius i, m
$r_{A,i}$	area-equivalent radius of a particle, m
$r_{f,i}$	fractal radius of a particle, m
r_m	mobility radius of a particle, m
t	time, s
u	velocity, m/s
$V_{i,j}$	van der Waals/viscous correction factor
v_1	volume of individual spherule, m^3
v_i	volume of the aggregate as if it were a sphere of uniform density, m^3
$\overline{v_p}$	mean thermal speed of a particle, m/s

Greek letters

$\beta'(L,\lambda)$	coagulation coefficient between particle of size L and λ, $1/m^3s$
δ_i	mean distance (m) used in the Fuchs interpolation formula, evaluated at the mobility radius
ω	quadrature weight

moment transport equations are unclosed. Thus the quadrature method that approximates the number density function using finite-mode representations is very efficient and has lower computational cost [2]. The quadrature method of moment (QMOM) was firstly presented by Ref. [29] for pure growth process and later applied to aggregation and condensation processes by Ref. [2] and to aggregation and aggregation-breakage processes by Refs. [24,25]. However, the modeling studies on aerosol processes mentioned above did not account for mixing and turbulence effects, i.e. they solved the GDE with the assumption of well-mixed space. Besides, the convection term, which associated with the impact of bulk air flow, was not included in those models. Generally, cooking process generates substantial amount of heat which results in strong buoyancy-driven flow [22]. This alteration of flow field would significantly affect the particle distribution. In order to consider the influence of the buoyancy flow on the particle distribution and to develop a more realistic model of particle transport process in the rooms with cooking process, the GDE must be coupled with turbulent computational fluid dynamics (CFD) modeling in the calculation of the particle temporal and spatial concentration.

The size of particles directly generated from cooking activities has been reported to be mainly in ultrafine range (particle size < 100 nm) and the particle number concentration reaches up to around 10^{12} m^{-3} [42,44]. Hence, coagulation plays an important role on the ultimate particle concentration in the indoor environment with undergoing cooking activities. Coagulation not only affects the number concentration but also the size distribution of particles which leads to different loss rate and ultimate exposure. The coagulation mechanisms can be divided into two categories: Brownian coagulation which is also known as thermal coagulation and coagulation owing to external forces which is known as kinematic coagulation [11]. The coagulation frequency functions for Brownian coagulation in continuum and free molecular regimes were firstly presented by Ref. [7]. There was no similar function for the transition regimes, so Fuchs further proposed an interpolation formula that has been generally accepted for the whole range of particle diameters. Actually, the interparticle forces like van der Waals force and viscous force have been considered to be particularly important in modifying coagulation kernel [17], since aerosol particle sizes are smaller or comparable to the mean free path of the air molecules. The effect of interparticle forces expressed in terms of a correction factor has been taken into account for coagulation in the continuum regime by Ref. [7] and in free molecular and transition regimes by Refs. [26,27]. In practice, the partial collided particles could form the fractal-like structures, rather than the spherical structures [21]. The effect of fractal geometry on coagulation could be considered in the Fuchs' interpolation formula by replacing coagulation radius with fractal radius, and the detailed treatment was found in the study of http://www.sciencedirect.com/science/article/pii/S0021850212000766 [28].

To date, very limited studies have focused on the indoor particle coagulation. Ref. [9] estimated the particle removal rates of the indoor sources in a laboratory room by employing Fuchs's interpolation formula to the calculation of spherical particle coagulation. Ref. [14] presented the detailed coagulation model with the consideration of the interparticle forces and fractal nature of soot particles. Moreover, this modified coagulation kernel was employed by Refs. [33] and [42] in their studies of ultrafine particles (UFPs) emitted by gas and electric stoves or ovens. However, dynamics of the indoor particle distributions in the foresaid studies were investigated by using experimental measurements and analytical solution with well-mixed assumption was adopted. And the convective effect caused by the buoyancy-driven flow has not been considered. The buoyancy of the heated plume and ventilation operation can actually produce the obvious velocity gradient in the bulk flow of a room with intensive cooking activities. Hence, the convective effect on coagulation is a significant factor which cannot be ignored in the study of the indoor particle concentration in model kitchens.

Our major objective in the present work is to employ an Eulerian method of moments which is coupled with computational fluid dynamics to solve the aerosol dynamics equation for computing the concentration and distribution of cooking-generated particles. The methodology was validated by experimental measurements conducted in a scaled chamber and in a full size environmental chamber. Besides, the modified Fuchs' coagulation kernel, which is a function of the particle size, Brownian motion, van der Waals