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Mathematical modeling of transport phenomena during waterpipe smoking—a parametric study

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ABSTRACT

Waterpipe (WP) smoking has spread worldwide and emerged as a global health issue in recent years. Yet only little is known on the details of transport phenomena and the compositions of smoke and particulates released during WP smoking. In this paper a general mathematical model is developed to study various processes occurring during the use of a WP. The model is used to assess the role of various design and operating conditions on the WP performance. In particular, the influence of water temperature, diameter of body pipe, depth of WP body immersed in the water, puff volume, water volume and puff frequency on the bubble hydrodynamics, the gaseous phase absorption and the removal of aerosols has been studied. Numerical results have indicated that the rate of gas absorption increases with the increase in depth of WP body immersed in the water, puff volume and the amount of water, and also with decrease in water temperature, diameter of body pipe and puff frequency. In addition, the removal of aerosols is improved with the increase in depth, radius and density of particles. The model results have also revealed that the major part of the pressure drop occurs in the water bowl.

Abbreviations

COHb carboxyhemoglobin
PAH polycyclic aromatic hydrocarbon
WP waterpipe

1. Introduction

The waterpipe (WP), also named shisha, narghile, argileh, etc., is a traditional aid for tobacco smoking in Asia and Northern Africa. However, in recent years, its use has spread to North America and Europe as well (Grekin and Ayna, 2012). A typical WP consists of a head, body, water bowl and hose. While a common opinion among users is that WP is relatively safe, it has been shown that WP can deliver large quantities of polycyclic aromatic hydrocarbons (PAHs), aldehydes, tar, nicotine, and carbon monoxide (Al Rashidi et al., 2008; Monn et al., 2007; Sepetdjian et al., 2008; Shihadeh and Saleh, 2005) to the user. In addition, waterpipe tobacco smoking significantly increased expired air CO, carboxyhemoglobin (COHb), mean plasma nicotine concentration and heart rate (Blank et al., 2011; Cobb et al., 2012; Eissenberg and Shihadeh, 2009).

When WP is used, air is drawn over the head and heated by the burning coals, a portion of it participating in the coal combustion, as evinced by the visible red glow that appears during each puff. The air and combusted gases are then passed through the tobacco, where due to hot air convection and thermal conduction from the coal, the mainstream smoke aerosol is produced. Smoke in the form of a dispersed phase of bubbles moves toward the continuous liquid phase in a water container or the bowl (Shihadeh, 2003). Because of the long path traversed by the smoke as it passes from the head, through the body, to the water bowl, and through the hose to the smoker, there are plenty opportunities for gas and particulate phase deposition, diffusion, and evaporation/condensation processes to occur (Shihadeh and Saleh, 2005).

The motion and removal of aerosols, suspended in the rising bubbles in a water bowl, is particularly important in WP. In fact the water bowl is the most important part of the WP filter, retaining 82–91% of the filtered tar. The remainder is absorbed by the walls of the body and the hose. The water filter retains the gaseous components according to their absorption coefficients (Rakower and Fatal, 1962). Monn et al. (2007) looked at the particle size emission from a WP and concluded that compared with cigarette, WP emits a much greater amount of ultrafine particles in the range of 0.02–1 μm, particularly from the burning charcoal.

Unlike the researches of cigarette smoking machine which are well standardized by Federal Trade Commission (FTC), the studies of WP smoking machines do not consider the effect of tobacco type (Moassel, Ajami, etc.), the contribution and the effect of charcoal replacement or movement, and the effects of different

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Nomenclature

A_B	single bubble surface, m^2
C	Cunningham correction factor
C_L	molar density of the bulk water, $kmol/m^3$
d_1	diameter of WP head, m
d_2	diameter of WP body, m
d_3	diameter of water bowl, m
d_4	diameter of hose, m
d_B	diameter of bubble, m
d_o	diameter of body pipe (at the end of the body which is immersed in water), m
d_T	diameter of tobacco particle, m
D	aerosol diffusivity, m^2/s
D_s	diffusivity, m^2/s
f	aerosol friction coefficient, kg/s
f_2	Moody friction factor in the WP body (part 2)
f_4	Moody friction factor in the WP hose (part 4)
g	gravitational acceleration, m/s^2
H_1	height of tobacco bed, m
H_2	height of body, m
H_3	depth of WP body immersed in the water, m
H_4	height of hose, m
H_s	Henry's law solubility constant of gaseous component in water, mol/m^3 pa
H_s^{θ}	Henry's law solubility constant of gaseous component in water at T^{θ}, mol/m^3 pa
k	Boltzmann's constant, J/K
K_{Hs}	Henry's law volatility constant of gaseous component in water, pa
K_{Ls}	liquid-phase mass transfer coefficient of component s, m/s
K_{Ls}^*	liquid-phase mass transfer coefficient of component s under the reference conditions, m/s
K_{Ls} (M)	K_{Ls} when parameter M is investigated and all other parameters are held constant, m/s
Kn	Knudsen number
K_r (M)	relative liquid-phase mass transfer coefficient when parameter M is investigated.
L_4	length of hose, m
M	the topographic and modeling parameters ($M=T$, d_o, H_3, V_{puff} and V_L)
M_G	smoke molar mass, kg/kmol
Mw_L	molecular weight of water, kg/kmol
Mw_s	molecular weight of gaseous component, kg/kmol
n	Puff number
n_{puff}	number of puff cycles in an average session
N	total number of aerosols in a bubble
N_0	total number of aerosols corresponding to zero path
N_a	total number of removed aerosols
N_A	Avogadro's number
N_{Bf}	frequency of bubble formation (i.e. the number of bubbles formed per puff)
N_{Bs}	amount of component s absorbed from single bubble during the rising period, kg
N_{puffs}	amount of component s absorbed during each puff, kg
N_{tot}	total absorption during the n puff, kmol
N_{tots}	absorption of component s during the n puff, kg
N_{ts}	absorption of component s during the smoking session, kg
N_{Bs}''	rate of mass transfer of component s, kg/m^2 s
N_{ts}^*	absorption of component s during the smoking session under the reference conditions, kg
N_{ts} (M)	N_{ts} when parameter M is investigated and all other parameters are held constant, kg
N_r (M)	Relative absorption during the smoking session when parameter M is investigated
P_{atm}	atmospheric pressure, pa
P_B	pressure inside the bubble, pa
Q_{puff}	flow rate of puff, m^3/s
R_B	radius of bubble, m
R_p	radius of particle, m
Re_o	Reynolds number
t_c	exposure time, s
t_{puff}	puff duration, s
T	temperature in the water bowl, °C
T_G	smoke temperature, K
T^k	temperature, K
T^{θ}	reference temperature, K
U_o	mean velocity at the end of the body which is immersed in water, m/s
U_1	mean velocity in the WP head (part 1), m/s
U_2	mean velocity in the WP body (part 2), m/s
U_3	mean velocity in the water bowl (part 3), m/s
U_4	mean velocity in the hose (part 4), m/s
U_k	mean velocity in part k = 1, 2, 3 and 4, m/s
U_B	bubble rising velocity, m/s
V_B	average volume of the detached bubble, m^3
V_L	water volume in the bowl, m^3
V_{puff}	puff volume, m^3
X_s	mole fraction of dissolved gaseous component in the water in equilibrium
X_{so}	mole fraction of gaseous component in water for initial of each puff
y_s	mole fraction of gaseous component in smoke
z	vertical, upwards coordinate, m

Greek symbols

α_d	Brownian aerosol removal coefficients, m^{-1}
α_i	inertial aerosol removal coefficients, m^{-1}
α_j	aerosol removal coefficients due to various mechanism j, m^{-1}
α_s	sedimentation aerosol removal coefficients, m^{-1}
α_t	total aerosols removal coefficient, m^{-1}
$\Delta_{sol}H$	the enthalpy of solution, J/mol
ΔP_1	pressure drop in the WP head (part 1), N/m^2
ΔP_2	pressure drop in the WP body (part 2), N/m^2
ΔP_3	pressure drop in the water bowl (part 3), N/m^2
ΔP_4	pressure drop in the WP hose (part 4), N/m^2
ΔP_k	pressure drop due to part k = 1, 2, 3 and 4, N/m^2
ΔP_{tot}	total pressure drop, N/m^2
ε_T	porosity of tobacco bed
ρ_G	density of smoke, kg/m^3
ρ_L	density of liquid, kg/m^3
ρ_p	density of aerosol, kg/m^3
μ_G	viscosity of smoke, kg/m s
μ_L	viscosity of water, kg/m s
v_G	kinematic viscosity of smoke, m^2/s
v_s	molar volume of the solute at normal boiling point, $m^3/kmol$
σ_L	surface tension of liquid, N/m
λ	mean free path of the gas molecules, m
τ_p	characteristic time, s
φ	association parameter of the solvent (= 2.26 for water as solvent)
φ_G	volume fractions of smoke
φ_L	volume fractions of water