Determination of the interfacial heat transfer coefficient between forced air and sand at Reynold's numbers relevant to smouldering combustion

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Marco A.B. Zanoni [a], José L. Torero [b], Jason I. Gerhard [a,*]

[a] Department of Civil and Environmental Engineering, University of Western Ontario, London, Ontario N6A 5B9, Canada
[b] School of Civil Engineering, University of Queensland, St. Lucia Campus, Brisbane 4067, Australia

A B S T R A C T

Heat transfer between flowing air and a fixed sand bed at low Reynold's number (i.e., $Re < 30$) is central to numerous natural and applied processes, including smouldering combustion. The most widely used correlation for the heat transfer coefficient (h_{sg}) predicts Nusselt numbers so high, it effectively presumes local thermal equilibrium for these systems; an assumption that has never been tested. In this work, twelve column experiments combined with numerical modelling quantify h_{sg} across a range of relevant sand grain sizes ($0.125 < d_p < 2.000$ mm) and air flow rates ($0.5 < Re < 31$). All of the sand properties were determined independently, with only h_{sg} determined via inverse modelling. A new empirical correlation for h_{sg} is obtained, $Nu = 0.001 (Re^{1.97} Pr^{1/3})$, which is then validated against two additional experiments. A newly developed criterion for assuming local thermal equilibrium is shown to be violated in all of these convection-dominated experiments and the extent of non-equilibrium between sand and air is quantified. The centerline temperatures are demonstrated to be sensitive not only to h_{sg} but also to a global heat loss coefficient quantified from the experiments in a novel manner. Overall, the new h_{sg} correlation is demonstrated to be reliable for predicting the interphase heat transfer in these systems and its application is expected to be valuable for a wide range of processes including smouldering.

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1. Introduction

Smouldering is defined as an oxygen-limited, flameless form of combustion with low temperatures and slow propagation rates relative to flaming [1]. It is a heterogeneous, exothermic chemical reaction between the (solid or liquid) reactive fuel and oxygen, using the heat released during the exothermic process to sustain the combustion front [1–4]. Traditionally, research on smouldering focused on porous organic solids, such as polyurethane foam and peat in the context of fire safety [5]. Examples include smouldering involved in residential, industrial, and forest fires and subsurface fires in coal seams.

Recently, smouldering has been developed as an engineering technology. Applications include liberating oil from shale [6–8], treating human feces [9], underground coal gasification [10], tire recycling [11], treating wastewater biosolids [12], and remediating contaminated soil [13–16]. In each case, smouldering is enabled by

the fact that the organic fuels are embedded in an inert porous matrix (e.g., rock, soil, sand). This matrix plays important roles, including: (i) its permeability permits oxygen transfer to the reaction zone by convection and diffusion [1,4,15,17], and (ii) its high heat capacity acts as a thermal reservoir, which recycles the released energy into the reaction. This energy efficiency enables the smouldering of fuels with low calorific values [18–20].

Generally, predictions of smouldering must take into account the transport of momentum, mass, and energy in the solid and fluid phases [21,22]. The transport of energy is dependent on the ability of the porous medium to store, conduct, and radiate heat, as well as convective transfer between phases. Modelling of energy generally follows one of two approaches: Local Thermal Equilibrium (LTE) or Local Thermal Non-Equilibrium (LTNE) [23–28]. In LTE, the local temperature of the solid and gas phases is assumed to be the same so only one energy equation is employed. In LTNE, this is not assumed, so the energy equation for each phase is solved:

$$(1-\phi)(\rho_s C_{p_s})\frac{\partial T_s}{\partial t} = (1-\phi)\frac{\partial}{\partial x}\left((k_s + k_{rad})\frac{\partial T_s}{\partial x}\right) - U\left(\frac{A_{s,c}}{V_c}\right)(T_s - T_\infty)$$
$$+ h_{sg}\left(\frac{A_{s,sp}}{V_{sp}}\right)(T_g - T_s) \quad (1)$$

* Corresponding author at: Department of Civil and Environmental Engineering, The University of Western Ontario, Spencer Engineering Building, Rm. 3029, London, Ontario N6A 5B9, Canada.
E-mail addresses: mbazelat@uwo.ca (M.A.B. Zanoni), j.torero@uq.edu.au (J.L. Torero), jgerhard@uwo.ca (J.I. Gerhard).

Nomenclature

Abbreviations

DSC	Differential Scanning Calorimetry
LM	Levenberg-Marquardt
LTE	Local Thermal Equilibrium
LTNE	Local Thermal Non-Equilibrium
NRMSD	Normalized Root-Mean-Square Deviation
REV	Representative Elementary Volume

Latin letters

a_v	surface area per unit volume, m^{-1}
A	cross-sectional area, m^2
A_s	surface area, m^2
Bi	biot number
C_p	specific heat capacity, $J\,kg^{-1}\,K^{-1}$
D	diameter of the column, m
d_p	particle diameter, m
E	energy, J
g	gravitational acceleration, $m\,s^{-2}$
h_{sg}	interfacial heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
h_v	volumetric heat transfer coefficient, $W\,m^{-3}\,K^{-1}$
H	height of the column, m
k	thermal conductivity, $W\,m^{-1}\,K^{-1}$
k_p	intrinsic permeability, m^2
l	Representative Elementary Volume length scale, m
L	system length scale, m
m	mass, kg
n	number of independent experiments
Nu	Nusselt number
P	pressure, Pa
Pr	Prandtl number
q	heat flux, $W\,m^{-2}$
Q	volumetric flow rate, $m^3\,s^{-1}$
r	radius of the column, m
Ra	Rayleigh number
Re	Reynolds number
S	objective function, K^2
t	time, s
T	temperature, K
T_∞	ambient temperature, K
u_g	Darcy Air flux, $m\,s^{-1}$
U	global heat loss coefficient, $W\,m^{-2}\,K^{-1}$
V	volume, m^3

Greek symbols

α	thermal diffusivity, $m^2\,s^{-1}$
δ_w	thickness of the thermal wave, m
μ	dynamic viscosity, Pa s
ν	kinematic viscosity, $m^2\,s^{-1}$
ρ_b	bulk density, $kg\,m^{-3}$
ρ_s	particle density, $kg\,m^{-3}$
ϕ	porosity
σ	Stefan–Boltzmann constant, $W\,m^{-2}\,K^{-4}$
σ_s	standard deviation, K
τ_{REV}	Representative Elementary Volume characteristic time, s
τ_p	particle-scale characteristic time, s

Subscripts/superscript

avg	average
c	cylinder
cond	conduction
conv	convection
exp	experimental
f	final
g	gas
gen	generation
h	heater
i	time step
in	inlet
j	thermocouple number
M	mean
max	maximum
min	minimum
num	numerical
0	initial
out	outlet
p	peak
rad	radiation
s	solid (quartz)
sg	solid/gas
sp	sphere
st	standard
T	total
w	wall

$$\phi(\rho_g C_{p_g})\frac{\partial T_g}{\partial t} + \rho_g C_{p_g} u_g \frac{\partial T_g}{\partial x} = \phi\frac{\partial}{\partial x}\left(k_g\frac{\partial T_g}{\partial x}\right) + h_{sg}\left(\frac{A_{s,sp}}{V_{sp}}\right)(T_s - T_g)$$

(2)

The two equations are linked by the interfacial heat transfer coefficient (h_{sg}), which dictates transfer between solid and gas phases. h_{sg} is multiplied by the surface area per unit volume assumed as perfect spheres ($A_{s,sp}/V_{sp} = 6(1 - \phi)/d_p$) [29]. The global heat loss coefficient (U) is multiplied by the surface area per unit volume of cylindrical column ($A_{s,c}/V_c = 2/r$). Note that source/sink terms would appear in Eqs. (1) and (2) if chemical reactions were taking place.

Analytical and numerical models of smouldering assuming LTE [7,18,20,29–37] and LTNE [21,22,38–45] have been extensively applied. It is suspected that LTNE is necessary to predict scenarios with forced air flow through hot sand. For example, high inlet gas velocities can decrease the solid temperature until smouldering quenches [1,38,46–52]. Thus, LTNE predictions require quantifying the thermophysical properties of both phases and h_{sg}.

The thermophysical properties of sand are important for a wide range of heat transfer applications beyond only applied smouldering. Sand's specific heat capacity (C_{ps}) and thermal conductivity (k_s) vary with temperature (T), porosity (ϕ), and particle diameter (d_p). Literature thermophysical properties for quartz sand are compiled in Table 1. The range of values reveal that these measurements need to be conducted with care and under relevant experimental conditions.

h_{sg} has been examined to predict heat transfer processes in a range of porous media including sand beds [62,63], sintered particles [64–66], spherical glass particles [67–69], ceramic foam [70–73], metal foam [74], and porous carbon foam [75]. h_{sg} is independent of the surface area per unit volume of the porous medium ($a_v = A_s/V$) (see Eq. (1)). When a_v is unknown, the results are reported in terms of a volumetric heat transfer coefficient ($h_v = a_v\cdot h_{sg}$) [70,71]. Analytical equations [23–26,42,66], inverse modelling [70,71], and experiments [66,70,71,76–83] have been used to derive empirical correlations for h_{sg} or h_v as a function of the parameters on which it depends, such as Reynolds number