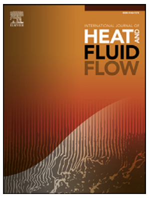
International Journal of Heat and Fluid Flow 66 (2017) 185–196

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

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



The relationship between external and internal flow in a porous body using the penalisation method

R. Aganetti[b], A. Lamorlette[a,*], G.R. Thorpe[b]

[a] Aix-Marseille Université, CNRS, Centrale Marseille, M2P2 UMR 7340, Marseille 13415, France
[b] Institute for Sustainability and Innovation, College of Engineering & Science, Victoria University, Melbourne, Vic 8001, Australia

ARTICLE INFO

Article history:
Received 19 January 2016
Revised 9 February 2017
Accepted 6 June 2017

Keywords:
Porous media
Numerical modelling
Penalisation method
Turbulence

ABSTRACT

Stockpiles of organic porous materials such as biosolids, coal, compost and woodchips are susceptible to spontaneous combustion. Flow fields within such materials are induced by buoyant forces and external agents such as the wind. However, the external forces may vary on a time scale of seconds, whereas the heat, mass and momentum processes within the porous medium may occur over timescales days or months. It would be computationally prohibitive to resolve all of the timescales, hence in this paper mean external forces are coupled to the flow field within stockpiles of biosolids by means of a penalisation method. It has been determined that four variables have a profound influence of the flow fields within porous media These are the velocity of the wind, the permeability of the porous biosolids, the angle of repose of the medium and aspect ratio of the stockpile. Four distinct flow regimes within the stockpiles have been identified. A correlation has been developed to assist managers of stockpiles, which relates mean velocities within the four flow regimes with a Darcy and Reynolds number, the aspect ratio and angle of repose. The correlation is accurate for two of the four flow regions identified, but the error in predicting the two remaining regions is relatively large. However, this error is expected to have minimal impact on estimating the time for spontaneous combustion to occur.

1. Introduction

Stockpiles of organic material such as biosolids (Poffet et al., 2008; Moraga et al., 2009; Zerlottin et al., 2013; Aganetti et al., 2016), coal (Chen, 1992; Carras and Young, 1994), woodchips (Ferrero et al., 2009) and compost (Sidhu et al., 2006; 2007; Luangwilai et al., 2010) are often subject to self-heating. This results from a coupling of mechanisms such as biological activity and oxidative reactions leading to increased local temperatures which can result in auto-ignition of the material (Rynk, 2000). Several numerical models have been developed and used to explore the factors that control the auto-ignition of self-heating material (Aganetti et al., 2016; Carras and Young, 1994; Ferrero et al., 2009; Luangwilai et al., 2010; Zambra et al., 2012). The real-life geometry of a stockpile does not directly lend itself to a two-dimensional approximation, however such an approximation enables the least ventilated region of the stockpile to be isolated (the middle of the pile) and considering that at the centre there is an absence of span-wise gradients due to symmetry, this geometry is a good candidate for a two-dimensional approximation. The processes occurring within a stockpile of self-heating material can be characterised as heat and mass transfer within hygroscopic porous media, and in which there are heat and mass sources. The thermal energy which accumulates within the pile is delicately balanced through diffusive and advective cooling, and when the heat generation can no longer be limited through these processes, thermal runaway occurs.

Since the contribution of cooling resulting from advection has been determined to be controlled by the permeability of the materials (Aganetti et al., 2016; Carras and Young, 1994; Nelson and Chen, 2007), the objective of this paper is to obtain a first estimate of how to characterise the advective flow inside a porous bulk material. It is expected that when the permeability is high, buoyancy driven flows will develop as a result of the internal heat generation, additionally a forced flow may be present due to pressure gradients resulting from an external flow impinging on the material (Carras and Young, 1994; Ferrero et al., 2009; Luangwilai et al., 2010). However, when the permeability is sufficiently low, it may not be necessary to take into account advective processes, in which case a purely diffusive model is adequate (Moraga et al., 2009; Zambra et al., 2012).

However, when it is deemed necessary to account for the advective contribution - particularly the forced convection resulting from an external flow - a time scale problem can arise between

---

[*] Corresponding author at: Aix-Marseille Université, CNRS, Centrale Marseille, M2P2 UMR 7340, Marseille 13415, France.

E-mail addresses: rachael.aganetti@live.vu.edu.au (R. Aganetti), aymeric.lamorlette@univ-amu.fr (A. Lamorlette).

http://dx.doi.org/10.1016/j.ijheatfluidflow.2017.06.003
0142-727X/

Nomenclature

A	Pile aspect ratio, [-]
$C_{1\epsilon}$	Constant, [-]
$C_{2\epsilon}$	Constant, [-]
C_{μ}	Constant, [-]
Da	Darcy number, [-]
h	Validation case porous region height, [m]
H	Pile height, [m]
k	Turbulent kinetic energy, [$\mathrm{m}^2 \cdot \mathrm{s}^{-2}$]
l	Validation case clear fluid region height, [m]
L	Length along top of pile, [m]
p	Pressure, [Pa]
R	Porous drag, [$\mathrm{kg} \cdot \mathrm{m}^2 \cdot \mathrm{s}^{-2}$]
Re	Reynolds number, [-]
S_{ij}	Rate of strain, [s^{-1}]
u	Field velocity, [$\mathrm{m} \cdot \mathrm{s}^{-1}$]
v^*	Validation case dimensionless velocity, [-]
V	Validation case reference velocity, [-]
y^*	Validation case dimensionless height, [-]

Greek symbols

α	Correlation parameter, [-]
β	Correlation parameter, [-]
γ	Correlation parameter, [-]
ϵ	Rate of dissipation of turbulence, [$\mathrm{m}^2 \cdot \mathrm{s}^{-3}$]
κ	Permeability, [m^{-2}]
μ	Dynamic viscosity, [$\mathrm{kg} \cdot \mathrm{m}^{-1} \cdot \mathrm{s}^{-1}$]
ν	Kinematic viscosity, [$\mathrm{m}^2 \cdot \mathrm{s}^{-1}$]
ϕ	Porosity, [-]
ρ	Density, [$\mathrm{kg} \cdot \mathrm{m}^{-3}$]
σ	Constant, [-]
θ	Angle of repose, [°]

Subscripts

A	Aspect ratio correlation parameter
critical	Critical
eff	Effective
ϵ	Rate of dissipation
f	Fluid phase
in	Inlet
k	Kinetic
o	Initial
out	Outlet
pile	Pile
ref	Reference value
surface	Pile surface boundary
t	Turbulent
θ	Angle of repose correlation parameter
μ	Viscosity

the internal self-heating processes and the external flow. In order to calculate the external flow over the pile, a small time scale, in the order of 10^{-2} s, is required, however, the physical processes of self-heating occur on a large time scale resulting from the biological and oxidative heating processes which have been observed to last for hours up to months (Poffet et al., 2008; Zerlottin et al., 2013). This time scale restriction can result in computationally expensive and lengthy simulations.

In this work we calculate the mean behaviour of the external flow field, and impose the result as a boundary condition or a fixed velocity field on the porous medium. This method of imposing the velocity has been implemented in previous studies of heat and mass transfer in self-heating compost piles (Luangwilai et al., 2010). However, in other models of self-heating of porous organic materials, such as coal (Carras and Young, 1994) and biosolids (Aganetti et al., 2016), a forced flow was neglected and only the buoyant flow was considered. Studies which have not accounted explicitly for the advective term include a model for woodchip piles (Ferrero et al., 2009) in which the advection was accounted for by means of an enhanced diffusion coefficient. Table 1 summarises a non-exhaustive number of previous works and the attention of each model with regard to the flow within the pile.

There has been much work reported on how a porous medium interacts with an external flow. Thus, there exist various methods for numerically simulating the flow in and around a porous media. Firstly, it must be determined whether the external flow is laminar or turbulent, then the permeability of the porous structure will determine whether or not turbulence will enter the porous zone, and finally if the flow in the porous region is determined to be laminar. The literature suggests that most research appears to focus on the asymptotic conditions, that is high Reynolds turbulent flow over a highly porous body, requiring inertial and turbulent forces to be resolved within the porous zone (Silva and de Lemos, 2003b; de Lemos, 2005), or a low Reynolds laminar flow with a purely Darcian flow within the porous zone (Silva and de Lemos, 2003a).

However, the problem presented here is a combination of turbulent flow over a porous body which has a relatively low permeability resulting in a Darcian flow in which inertial effects are negligible. Finally, it must be noted the importance of considering the effects of the porous fluid interface at the boundary of the porous structure. Beavers and Joseph (1967) carried out the seminal experimental study of flow at the interface of a clear fluid and a porous medium. Their work indicated that a no-slip boundary condition on the velocity exists at the interface, but they did not develop a definitive procedure for its quantification. Ochoa-Tapia and Whitaker (1995a) exploited the methods of volume averaging to demonstrate that a stress jump exists at the interface, and they compared their model with experimental results (Ochoa-Tapia and Whitaker, 1995b).

This model has been adopted and modified in many other studies of flow in and around a porous body (Silva and de Lemos, 2003b; de Lemos, 2005; Silva and de Lemos, 2003a; de Lemos and Silva, 2006; Chandesris and Jamet, 2009; Mößner and Radespiel, 2015). However, according to Ochoa-Tapia and Whitaker (1995b), an empirical jump coefficient assumes a wide range of values. Furthermore, there is no clear trend associated with permeability, porosity or types of material, and it is therefore not possible to select a value for this study without resorting to experimental studies on the material under consideration. Given that the objective of this paper is to obtain a first estimate of how to characterise the flow inside a porous bulk material based on the external flow and other variables it seems reasonable to assume mass continuity across the interface and to allow the Darcian resistance term in the porous medium to account for the change in stress at the porous/fluid interface.

In previous work, carried out by Aganetti et al. (2015), efforts were made to establish a correlation between a potential external flow and the internal flow of a stockpile of porous self-heating material, in order to prescribe an imposed velocity to account for the forced flow resulting from the external flow. A correlation between dimensionless velocity, Darcy and Reynolds numbers was developed by carrying out dimensional analysis on the one-dimensional Darcy solution. The correlation was expected to be linear and when fitted with a power law, this was justified with the exponents being very close to unity.

This paper presents an extension of the work presented by Aganetti et al. (2015) and the correlation is extended to include additional dimensionless parameters. The revised correlation depends on the external flow, the physical properties and geometry of the pile. This is achieved using an open source computational fluid