Applied Thermal Engineering 106 (2016) 361–370

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Measurement of convective heat transfer coefficients in a randomly packed bed of silica gel particles using IHTP analysis

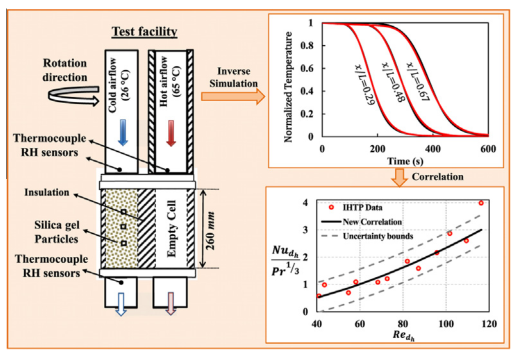
Mohamadreza Naghash [a], Farhad Fathieh [a,*], Robert W. Besant [a], Richard W. Evitts [b], Carey J. Simonson [a]

[a] Department of Mechanical Engineering, University of Saskatchewan, 57 Campus Drive, Saskatoon, SK S7N 5A9, Canada
[b] Department of Chemical & Biological Engineering, University of Saskatchewan, 57 Campus Drive, Saskatoon, SK S7N 5A9, Canada

HIGHLIGHTS

- A novel facility monitors the transient thermal response of porous gel packed beds.
- The convective heat transfer coefficient is estimated using inverse simulation.
- Good agreement is seen in experimental and simulated temperature profiles.
- A correlation for Nu versus Re with lower uncertainty is proposed.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 30 July 2015
Revised 18 May 2016
Accepted 4 June 2016
Available online 7 June 2016

Keywords:
Convective heat transfer coefficient
Packed bed
Porous particle
Transient testing

ABSTRACT

The purpose of this research is to determine the convective heat transfer coefficient (h_t) for airflow through two randomly packed beds of microporous silica gel particles of nearly uniform diameter (i.e., for the average diameter of 1.60 and 2.58 mm). The experimental test facility was developed to induce a transient step change in the inlet uniform airflow while the temperature was measured at several locations within the silica gel beds (x/L = 0.29, 0.48, 0.69). The transient test data were simulated numerically using the volume averaging method for air flow through a homogeneous packed bed of particles for a range of Reynolds numbers ($40 < Re_{dh} < 100$). The convective heat transfer coefficient was determined by using the numerical inverse method to minimize the difference between the simulated and experimental temperature profiles. The sensitivity analysis stated that the thermocouple placed at the middle of the test section (x/L = 0.48) had the highest sensitivity during the first 400 s of transient testing. Using the h_t values obtained by the inverse calculations, a good agreement is obtained within the experimental uncertainty limits for the experimental and numerical temperature temporal profiles at different locations within the beds; but the agreement is best using the transient temperature data at x/L = 0.48. Based on the h_t values, a new correlation between Nusselt number and Reynolds number is presented with lower uncertainty (the maximum uncertainty of ±30%) compared to the correlations in the literatures. It was found that the proposed correlation is in agreement with the data in literature within their uncertainty bounds.

* Corresponding author.
E-mail address: Farhad.Fathieh@usask.ca (F. Fathieh).

http://dx.doi.org/10.1016/j.applthermaleng.2016.06.027
1359-4311/

Nomenclature

$A_{sf,v}$	specific volumetric surface area, m^2/m^3
C_p	specific heat capacity, J/(kg K)
d	diameter, mm
d_h	hydraulic diameter, m
d_p	particle diameter, mm
h_t	convective heat transfer coefficient, W/(m^2 K)
k	thermal conductivity, W/(m K)
k_{eff}	effective thermal conductivity of the porous bed, W/(m K)
L	length of the particle bed, m
N	number of measurement readings
Nu	Nusselt number
P	pressure, Pa
Pr	Prandtl number
R	gas constant, J/(kg K)
Re	Reynolds number
R^2	the coefficient of determination
S	objective function, K^2
T	temperature, K
t	time, s; student t
t_n	vector of time, s
U	uncertainty
U_d	interfacial velocity, m/s
U_p	pore velocity, m/s
$\bar{X}$	reduced sensitivity coefficient, K
$\hat{X}$	sensitivity coefficient matrix
x	position, m
Y	measured temperature vector, K

Greek symbols

β	unknown parameter
θ	normalized temperature
δ	differential change
ε	porosity
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3

Subscript

air	air flow
bed	particle bed
e	external
g	gaseous phase
i	internal; time node
p	particle
s	solid phase (pure solid silicagel (SiO_2) + internal gaseous phase)
silica	pure solid silicagel (SiO_2)

1. Introduction

Thermal convection processes in particle beds are ubiquitous in many industries for processing food products, pharmaceuticals, bulk fertilizers, construction particles, granular plastics, metallurgical particles, etc. Often these particles are porous at the microscopic level and their internal properties appear to be heterogeneous for the porous organic, agglomerated, or crystalline solid particles with internal air spaces occupying much of their volume. In a bed of particle, convection within the spaces between particles is commonly used during thermal processes. Desiccant particles, such as silica gel, are widely used for drying processes due to their large specific capacity for moisture sorption and low regeneration temperature [1]. For instance, natural gas moisture removal is most often achieved by passing the gas through a bed of dry desiccant particles which are then regenerated by a heated air flow [2]. As another application for air-to-air energy recovery, silica gel and molecular sieve particles coated on closely spaced aluminum or plastic flow channels of regenerative wheels. The coated wheel matrix is responsible for heat and moisture transfer between steady supply and exhaust airflows [3].

Attention to the convective heat transfer coefficient in porous media has increased in recent years because of the wide usage of porous materials in the cooling of electrical systems, combustors, fixed-bed reactors, and compact porous heat exchangers [4]. Although transport properties of particle beds are often known to be transient for heat and mass transfer process; but, the convective heat and mass transfer coefficients are nearly constant for constant flow rates and fixed bed geometry.

Kays and London [5] presented one of the first well known correlations for convective heat transfer coefficient (h_t) for flow through a particle bed. Whitaker [6] developed correlations for the Nusselt number versus Reynolds number when a gas flow passes through particle beds of spherical particles and cylindrical particles during quasi-steady state conditions. For bed Reynolds numbers larger than 20, he found that the Nusselt number is a function of the Reynolds and Prandtl numbers. For fully developed flow within cylindrical tubes or ducts, Shah and London [7] showed that the Nusselt number is a function of the Reynolds number, Prandtl number, the type of boundary condition (e.g., constant wall temperature or heat flux) and cylindrical type geometry of the flow channel (e.g., cylindrical, elliptical, hexagonal, square, rectangular, parallel plate, or triangular). For fully developed laminar flow in a cylindrical type flow channel with a constant wall temperature or heat flux, the Nusselt number will be a constant. For the entrance region of flow, both the Graetz number and the Prandtl number will be factors that will alter the value of Nusselt number. For steady bulk flows and small temperature changes in a porous media, the Prandtl number and Reynolds number can be considered to be a constant. Kar and Dobbs [8] investigated the internal heat transfer coefficient of porous metals experimentally and presented a correlation for Nusselt number versus Reynolds number for porosity up to 0.65 in the Darcian regime of the airflow ($Re < 10$). Peng et al. [9] developed a correlation to find the convective heat and mass transfer coefficients in order to simulate the heat and mass transfer in a packed bed of potash particles that were exposed to humid airflow in the range of $20 < Re < 100$. Due to large uncertainties in their experimental data at low Reynolds number, their correlation was not successful to correlate constant Nusselt number at $Re < 5$.

Over the past decade, researchers employed numerical simulation to obtain the convective heat transfer coefficient in packed beds for different bed geometries at various operating conditions. Jiang et al. [4] studied the convective heat transfer coefficient between a sintered microporous media (particle diameter of 0.2 mm) and airflow by using both numerical and experimental methods. They considered that the temperature gradient in the solid phase is negligible in comparison with the temperature gradient in the gaseous phase. They found an experimental graph Nusselt number versus Reynolds number for low Reynolds numbers ($Re < 10$) which was in agreement with their one-dimensional numerical model. Nie et al. [10] studied temperature and moisture