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Effect of packing density on thermal properties of granular activated carbon packed bed by using of inverse heat conduction method

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ABSTRACT

The ability of granular activated carbon (GAC) to adsorb large mass of refrigerant gases makes it ideal for use in thermal compressor. In order to make thermal compressor economically viable, the size must be reduced and for that reason thermal responses should be increase as much as possible during heating and cooling process. This paper investigates the effect of GAC bed density on the thermal transient responses when a sudden change in temperature is imposed on wall of a test sample reactor. The test sample consists of 1” OD stainless steel with 0.71 [mm] thickness and 200[mm] length that is loaded with compacted granular activated. The granular carbon used is 208C (coconut shell base) with 13×30 mesh size and provided by ‘Chemviron Carbon Company’. To find the heat transfer coefficient of the contact wall/packed carbon (h) and packed bed thermal conductivity (k) a numerical inverse heat conduction method is used in conjunction with an iterative process based on minimizing the Mean Square Error (MSE) from measured temperatures. Experimental work is carried out by measuring the wall and centre temperatures of submerged sample in a temperature controlled water bath at around 85 [^{o}C]. Five samples with the packed bed density ranging from 500 [kg/m^3] to 800 [kg/m^3] were tested and the results show a quasi-linear increase of both thermal conductivity (k) and heat transfer coefficient of the contact wall/packed carbon (h) with the packed bed density: 0.15 [W/m.K] < k < 0.45 [W/m.K] and 150 [W/m^2.K] < h < 1400 [W/m^2.K].

INTRODUCTION

The best estimation of packed bed thermal properties such as wall/packed heat transfer coefficient (h) and thermal conductivity (k) are essential for optimizing bed cycling time of adsorption generator therefore cost effective design of thermal compressor. The first step the work is mainly focused on packed inert bed (no refrigerant is used there is adsorption or desorption process involved). The method to estimate the thermal properties from measured temperature change in packed bed is considered as an inverse problem. Heat transfer mechanisms through the heterogeneous granular carbon packed bed are: conduction through the grain, conduction through the grain to grain contact area, conduction and convention through the gas phase and radiation heat transfer from grain surface and void [1-3]. However, the overall heat transfer in such a heterogeneous media is usually modelled by conduction heat transfer with parameters as apparent [4].

Estimation of thermal properties is very sensitive to the measured quantities [1, 4] and several methods are available in literatures. In general, the thermal conductivity may be measured by either steady state methods or unsteady (transient) methods. Steady state method generates the static temperature field inside the specimen and measures the thermal conductivity directly while the transient method generates dynamic temperature field inside the specimen. The specimen temperature must be uniform. Then a small disturbance on the form of step-wise function is applied to the specimen and measures the thermal conductivity indirectly via the thermal diffusivity.

The guarded thermal flow meter is one of methods that could be used in steady state situation to measure the thermal conductivity according to the standards such as BS874 or ASTM E1530. There are numerous manufacturers of guarded thermal flow meter: Anter Instrument Corporation is an example with the Anter Quickline-10 machine [5]. Providing the stable higher density than loos density is very difficult and estimation of heat transfer coefficient of the contact wall/packed carbon is not reliable as well. The contact between wall and pack of carbon at both side of heater and cooler is not uniform and it has a serious effect on the parameter measuring. A hot wire method is one of methods that could be used in transient situation and it is much less sensitive and reliable to measure the material thermal properties [6-8]. Laser flash is another transient method to measure material thermal properties while this technic requires relative complex instrument and thin sample [9]. A simple measuring technique is based on tracing the cylindrical sample thermal responses to the suddenly change on the temperature at the boundary of sample [4, 10] and inverse numerical method [11]. The accuracy of parameter estimation is strongly influenced by the difference between the real and ideal assumption boundaries. The method used in this research similar to the one described with the key advantages of measuring the temperature at a boundary such a sample external wall. Furthermore the proposed technique will lead to identify both thermal conductivity (k) and heat transfer coefficient of the contact wall/packed carbon (h) with various packed bed densities.

NOMENCLATURE

k	[W/m.K]	Thermal conductivity of desire GAC packed
h	[W/m^2.K]	heat transfer coefficient of the contact wall/packed carbon
T	[^{o}C]	Temperature
k	[W/m.K]	Thermal conductivity
r	[m]	Sample cylinder radiuses
α	[m^2/s]	Thermal diffusivity
m_V	[kg]	Carbon mass for the specific volume
A	[m^2]	The domain area for nodal energy flow
MSE		Mean Square Error
ρ	[kg/m^3]	Carbon packed density
Cp	[J/kg.K]	specific heat
dt	[s]	Time increment
dr	[m]	Radius increment
dz	[m]	Sample cylinder length
Bi		Biot number
Fo		Fourier number

Subscripts

1	Represent the node one on a carbon packed surface
i	Represent the node number, where i=1,2,…, N
n	Represent the time
N	Maximum number of nodes.

EXPERIMENTAL SET-UP DESCRIPTION

The granular activated carbon (GAC) is 208C (coconut shell base) with 13×30 US sieve mesh size and provided by ‘Chemviron Carbon Company’.

To determine the thermal properties of a sample, the experimental method has been used based on the existing transient method [2, 3]. The experimental setup includes water temperature controlled bath, K-type thermocouples, stainless steel tube containing packed activated carbon, data logger and PC. Five test samples are manufactured: each consists of stainless steel tube with 1” outer diameter, 0.71 [mm] thickness and 200 [mm] length that is loaded with packed activated carbon and sealed in both ends (with provision for a thermocouple placed in the centre as illustrated in **Figure 1**). The five test samples have the carbon packed density of 546.7 [kg/m^3], 661.9 [kg/m^3], 707.7 [kg/m^3], 749.8 [kg/m^3] and 768.1 [kg/m^3] respectively. There are five thermocouples associated with set-up and allocated at following positions as shown in **Figure 2**: one placed at the centre of tube to measure the temperature changes of the activated carbon, one placed on the outside tube wall and other threes allocated in water bath at different heights to check the uniformity of the temperature. 1/8” outer diameter stainless steel tube (**Figure 1**) with 3 mm inner diameter allocated at middle of container tube as access of the centre thermocouple. All thermocouples are K-type with insulated junction and 1 mm diameter stainless steel sheath.

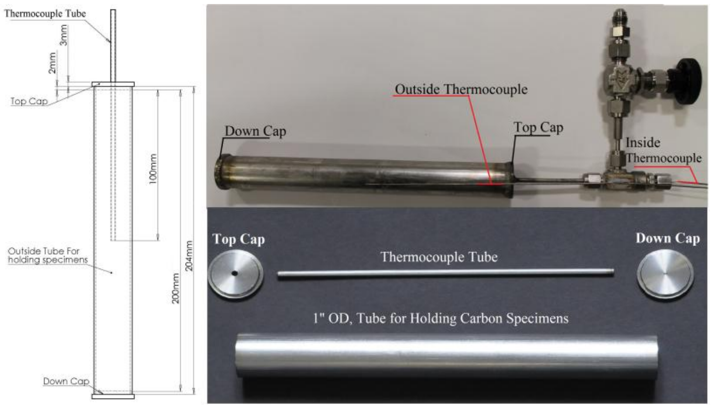

Figure 1 Sample holder dimensions and fabricated model.

Methodology:

a) Experimental procedure

The experimental procedure consists of suddenly plunge the sample that was initially at ambient temperature - into hot water (about 85[^{o}C]). All temperatures are scanned and stored throughout the test with a selected frequency of 0.015 [second] on the data logger.

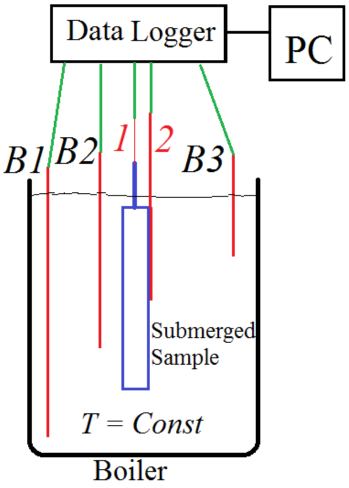

Figure 2 Measurement set-up, water temperature controlled bath with belt-in thermostat, allocated thermocouple in bath (*B1*, *B2* and *B3*), sample centre thermocouple (*1*), sample outside thermocouple (2).

b) Numerical method

Estimation of thermo-physical properties from the experiment data will use two steps. The first step is the elaboration direct explicit numerical method based on energy balance laws aimed to determine the transient temperature profile $T(r_N, t)$ of the material. Second step is the inverse problem which is including an optimization and computational algorithm: both thermal conductivity (k) and heat transfer coefficient of the contact wall/packed carbon (h) will then be identified in the course of this process by comparing the model predictions and the experimental data through the optimization of the mean square error (MSE):

$$MSE = \frac{1}{n}\sum_{i=1}^{n}\left(T_{calculated\ i} - T_{\mathrm{experimental}\ i}\right)^2 \qquad (1)$$

b.1) Internal Node:

Internal section modelling (packed carbon only): This is illustrated in **Figure 3.**

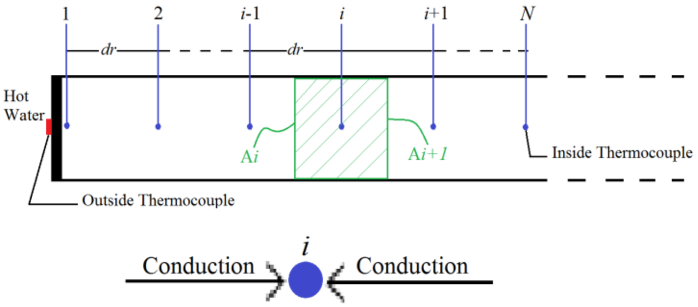

Figure 3 Domain discretization for the energy balance at the carbon packed inner node. Conduction heat, areas that delimit the controlled volume (*Ai*, *Ai+1*), *dr* is the radial increment.

The energy balance for internal node is:

$$q_{\underset{Left\ Side}{conduction}} + q_{\underset{RightSide}{conduction}} = m_V c_p \frac{\partial T}{\partial t} \qquad (2)$$

Or in the discretised form of:

$$kA_i\left(\frac{T_{i-1}^n - T_i^n}{dr}\right) + kA_{i+1}\left(\frac{T_{i+1}^n - T_i^n}{dr}\right) = \rho V c_p \frac{(T_i^{n+1} - T_i^n)}{dt} \qquad (3)$$

m_v is carbon mass for the specific control volume which is display on **Figure 4**. Then replace the carbon mass calculated from density and controlled volume of specific area. The areas and volume are defined as:

$$\begin{cases} A_i = 2\pi\left(r_i + \frac{dr}{2}\right)\Delta z \\ A_{i+1} = 2\pi\left(r_i - \frac{dr}{2}\right)\Delta z \\ V_i = 2\pi\, r_i\, \Delta z \times dr \end{cases} \qquad (4)$$

By substituting equation (4) in equation (3) and rearrange it becomes:

$$T_i^{n+1} = \left[\frac{Fo}{r_i}\left(r_i + \frac{dr}{2}\right)\right] T_{i-1}^n + [1 - 2\,Fo]T_i^n + \left[\frac{Fo}{r_i}\left(r_i + \frac{dr}{2}\right)\right] T_{i+1}^n \qquad (5)$$

Where:

$$Fo = \frac{\alpha dt}{dr^2} \qquad (6)$$

This non-dimensional number which is called Fourier (*Fo*); and defined as the ratio of heat conduction to the rate of thermal energy storage.

b.2) Outer Boundary Node:

Boundary section modelling (tube internal wall/ packed carbon): This is illustrated in **Figure 4**. Due the higher thermal conductivity of stainless steel (typical values 17 [W/m.K]) and more importantly the small wall thickness (0.71 [mm]), it is appropriate to assume both tube external and internal wall temperatures are identical.

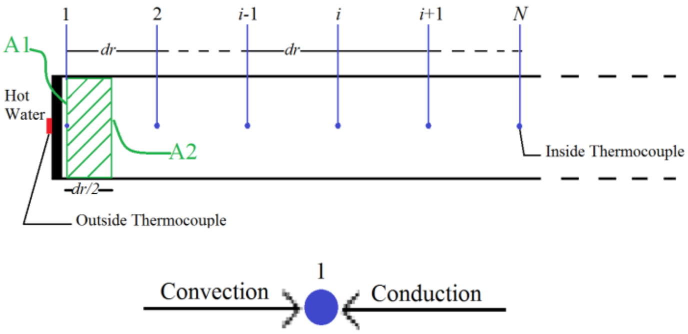

Figure 4 Domain discretization for the energy balance at the carbon packed surface node (outer boundary node).Contact internal wall/packed carbon heat transfer, conduction heat, areas that delimit the controlled volume (*A1*, *A2*), *dr* is the radial increment.

The energy balance for outside boundaries nodes is:

$$q_{\mathrm{convection}} + q_{\mathrm{conduction}} = m_V c_p \frac{\partial T}{\partial t} \qquad (7)$$

Or in the discretised form of:

$$h\,A_1(T_\infty^n - T_1^n) + k\,A_2\left(\frac{T_2^n - T_1^n}{dr}\right) = \rho V_1 c_p \frac{(T_1^{n+1} - T_1^n)}{dt} \qquad (8)$$

Where:

$$\begin{cases} A_1 = 2\pi\, r_1\, \Delta z \\ A_2 = 2\pi\left(r_1 - \frac{dr}{2}\right)\Delta z \\ V_1 = A_1 \times \frac{dr}{2} = 2\pi\, r_1\, \Delta z \times \frac{dr}{2} \end{cases} \qquad (9)$$

By substituting equation (9) in equation (8) and rearranging it becomes:

$$T_1^{n+1} = (2\,Fo\,Bi)\,T_\infty^n + \left[\frac{2\,Fo}{r_1}\left(r_1 - \frac{dr}{2}\right)\right] T_2^n + \left[1 - 2\,Fo\,Bi - \frac{2\,Fo}{r_1}\left(r_1 - \frac{dr}{2}\right)\right] T_1^n \qquad (10)$$

Where:

$$Bi = \frac{hdr}{k} \qquad (11)$$

This non-dimensional number which is called Biot (*Bi*) and equal to the ratio of heat transfer resistance inside the packed bed to the thermal resistance of the boundary layer.

b.3) Centre Point or Inner Boundary Node:

Centre node (inner boundary node) is another part of boundary section that is illustrated in **Figure 5**.

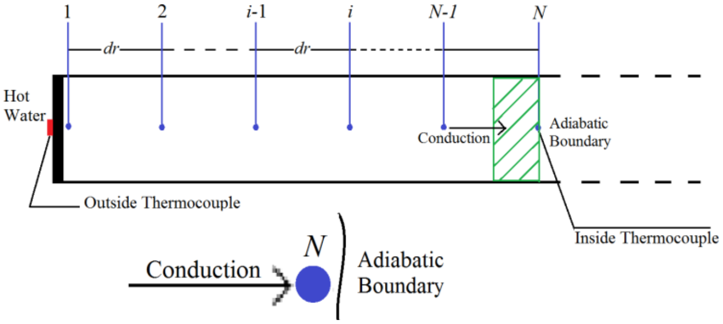

Figure 5 Domain discretization for the energy balance at the carbon packed centre node (inner boundary node). Conduction heat, no heat generation at centre node (*N*) and specific volume, *dr* is the radial increment.

By assuming the adiabatic boundary, the energy balance for centre node is:

$$q_{\text{conduction}} = m_V c_p \frac{\partial T}{\partial t} = 0 \qquad (12)$$

This means that on the inner boundary we have:

$$T_N = T_{N+1} \qquad (13)$$

EXPERIMENTAL RESULT AND ANALYSIS

In this work, the numerical approach is solved and optimized by using the program that is written in MATLAB R2012b. In order to process the iteration process, the time increment is set as 0.3 second and the length step (dr) in radial direction is set as 0.753 [mm].

Figure 6 and **Figure 7** show the temperature profiles with minimum (546.7 kg/m^3) and maximum (768.1 kg/m^3) densities respectively. The gap between both experimental data and model predictions of the temperature in the centre is well minimised. **Figure 8** illustrates multiple values of MSE that were explored for first sample (Density is 546.7 kg/m^3) in a range of $0.08 < k < 0.2$ with an increment of 0.001 [W/m.K] and $90 < h < 200$ with an increment of 1 [W/m^2.K]. For particular density the minimum of *MSE* is obtained 0.2358 from minimization process. All the samples were tested and the final results of the thermal conductivity (k) and heat transfer coefficient of the contact wall/packed carbon (h) identified are summed up in Table 1. Overall, fairly good fit with a minimum *MSE* is obtained for each density.

Density [kg/m^3]	K [W/m.K]	h [W/m^2.K]	MSE
546.7	0.175	143	0.2358
661.9	0.361	296	0.2272
707.7	0.381	499	0.0561
749.8	0.384	989	0.1434
768.1	0.421	1284	0.1478

Table1 Thermal conductivity (k) and heat transfer coefficient of the contact wall/packed carbon (h).

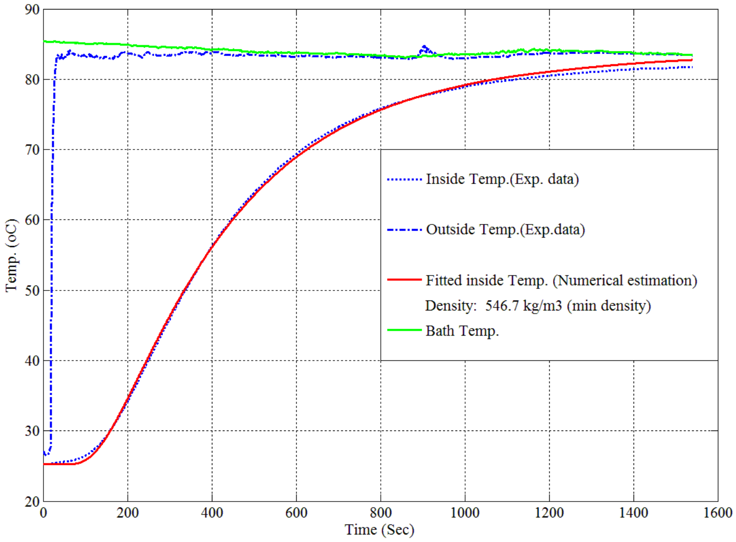

Figure 6 Temperature profiles with the packed density of 546.7 [kg/m^3]: k = 0.175 [W/m.K] and h =143 [W/m^2.K].

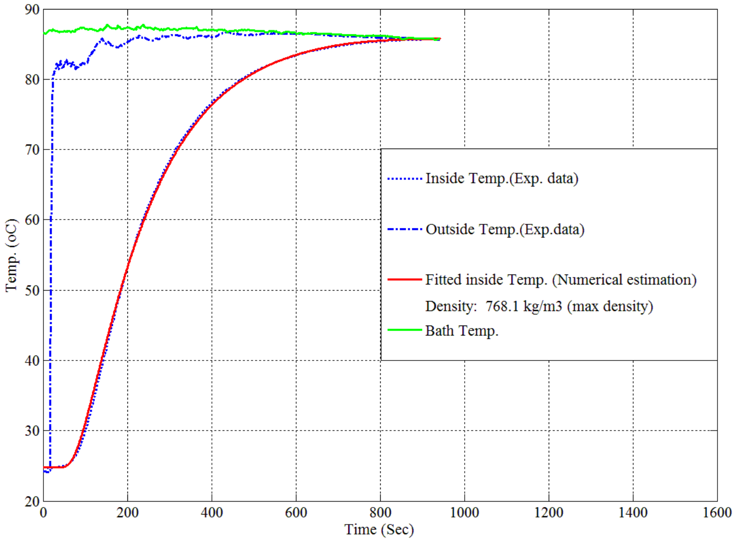

Figure 7 Tempereture profiles with the packed density of 768.1 [kg/m^3]: k = 0.421 [W/m.K] and h = 1284 [W/m^2.K].

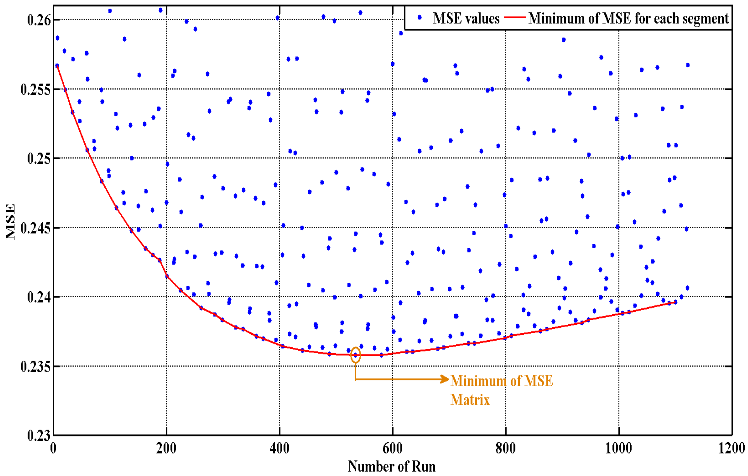

Figure 8 MSE values for first sample (546.7 kg/m^3).

Figure 9 and **Figure 10** show both thermal conductivity (k) and heat transfer coefficient of the contact wall/packed carbon (h) function of packed carbon density respectively. As expected both thermal conductivity (k) and heat transfer coefficient (h) increase quasi-linearly with the density. In fact high the backed density high will be both contact surface between the carbon grains and contact surface between the carbon grains and tube inner wall.

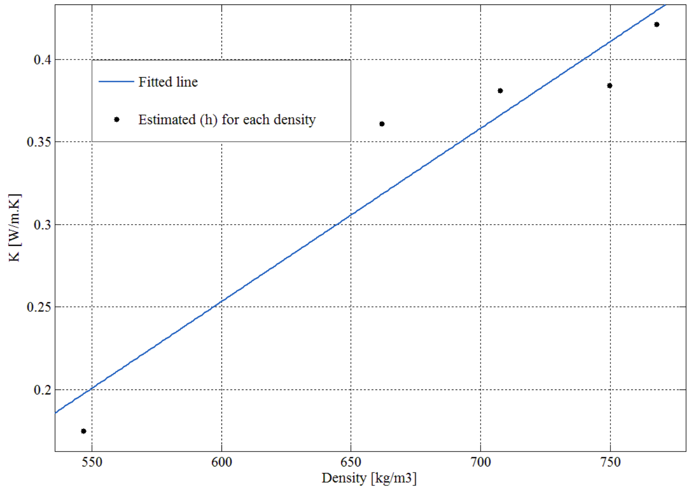

Figure 9 Estimated thermal conductivity versus sample packed density.

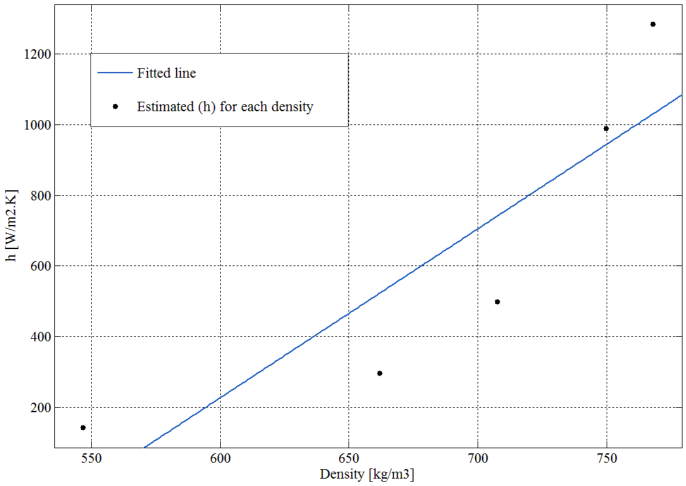

Figure 10 Estimated heat transfer coefficients of the contact wall/packed carbon versus sample packed density.

CONCLUSION

The heat transfer coefficient of the contact wall/packed carbon (h) and packed bed thermal conductivity (k) have been estimated using a numerical inverse heat conduction method associated an iterative process based on minimizing the Mean Square Error (MSE) from measured temperatures.

For the five test samples with the packed bed density ranging from 500 [kg/m^3] to 800 [kg/m^3] the results show a quasi-linear increase of both thermal conductivity (k) and heat transfer coefficient of the contact wall/packed carbon (h) with the packed bed density: 0.15 [W/m.K] < k < 0.45 [W/m.K] and 150 [W/m^2.K] < h < 1400 [W/m^2.K].

AKNOWLEGMENTS

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