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THEORETICAL AND EXPERIMENTAL INVESTIGATION OF HEAT TRANSFER IN GAS - SOLID PACKED BEDS

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Abstract

The number of investigations on convective heat transfer through a packed bed has been on the rise during the past decade. Many thermal engineering systems are in need of a better understanding of forced convection through packed bed. Such applications include: compact thermal collector-storage systems, drying processes, heat exchangers, grain storage, and catalytic reactors. The packed bed has many applications in several industry fields, especially heat exchangers that use this technique. An 8 x 8 cm square packed bed facility has been designed, constructed and assembled with a view to perform heat transfer studies under hot conditions. The aluminum of equivalent diameter 5 mm is used as packing material. The experiments were carried out for different bed depth and different gas velocity. The used gas is hot air and it is entered to test section at 50 ^{0}C. The bed temperature is measured with time. The present work aims to construct a simple experimental procedure and equations for predicting the gas to particle heat transfer coefficient of packed beds. An attempt is made to calculate this coefficient at different Reynolds numbers. In the present work Reynolds number varied from 315 to 455. The calculation method in the present work is based on bed temperature measurements and simple energy balance. A logarithmic mean temperature difference method is used. Nusselt number obtained from the literature is represented versus those calculated from the proposed model. Discrepancies were found. Consequently, the difference in experimental conditions used to establish these correlations modifies values of calculated Nusselt numbers. A reasonable agreement was found with the previous work. Also FEHT (**F**inite **E**lement **H**eat **T**ransfer Code) model is used to compare the experimental results. FEHT results are compatible with the present work results.

Keywords: Packed Bed; Heat Transfer; Thermal Storage.

1. Introduction

Packed bed columns are the best type of apparatuses, from thermodynamical point of view, for carrying out of mass and heat transfer processes between gas and solid phase. It is because of all types of highly effective apparatuses, they operate as near as possible to the conditions of countercurrent flow, i.e., at maximum driving force for given initial and end concentrations of the two phases and a given ratio between their flow rates [1].Packed beds have many applications in the chemical processing industry. For example, packed beds are used in reactors, separators, dryers, filters, and heat exchangers. The heat transfer throughout a packed bed can have a significant effect on the performance of the equipment. Therefore, it is important to better understand the heat transfer through packed beds which has led researchers to have an increased interest in the subject area. This led to a wide ranging research work aimed at understanding the in-bed processes in order to develop suitable models and correlations. So these correlations can be used in the design and control of large scale commercial packed bed [2]. The distinctive features of most of these operations in chemical industry were the use of solid granules in a fine powder form and consequent low gas velocities. Hence the research concentrated on studying the characteristics of fine particle beds. The awareness that the fluid dynamics in the bed controlled the other in bed processes resulted in a vast literature on almost every aspect of packed bed. The influence of temperature, gas velocity, particle size and size of distribution, bed height, bed diameter, distributor type, and geometry of internal baffles have been extensively studied and the knowledge is still being updated and improved upon. Several theories on bed dynamics have been proposed and is still being refined with new knowledge being gained every year. Side by side a development took place with the active and enthusiastic cooperation of industrial users. The technology, still under continuous development, being improved on the basis of the extensive experience gained over the past four decades, has now found useful application in every aspect of the chemical industry [3].One of the important areas of intense research in packed bed has been the heat transferred from the hot gas to the bed. There have been a few experimental investigations into heat transfer in this area. Correlations that have been proposed to describe the experiments have included only a small number of the significant variables, and describe only a small fraction of the published experimentation. The fundamental difficulty is the large number of physical variables that might be expected to affect the rate of heat transfer. The rate of heat transfer from depends upon the temperature difference between the gas and solids in the immediate neighborhood, gas velocity, density, heat capacity, thermal conductivity, particle size distribution, bed depth, distributor type and geometrical characteristics. All three modes

(Conduction, convection, and radiation) of heat transfer are relative to process associated with the bed of particles. The relative importance of each mode depends upon circumstance [4]. The particles to gas heat transfer coefficient is a key parameter to quantify heat transfer. In fact, a considerable amount of study has been carried out to evaluate this coefficient[2]. Wakao and Kaguei [5] provide a comprehensive review of the evaluation of the particle to fluid heat transfer coefficient. Ranz and Marshall [6] proposed the well-known correlation of this coefficient for spherical particle on the basis of a wide variety of experimental data on the evaporation of liquid droplets in air. Bird et al [7] gave a set of heat transfer correlations for a packed bed of spherical and cylindrical particles. Rowe and Claxton [8] presented a Nusselt number correlation by measuring experimentally heat and mass transfer between the sphere and identical fixed spheres. Jingzhu et al [9] measured particle to gas heat transfer coefficient from one-shot thermal responses in packed beds of glass beads air system in the range of Reynolds number for 5 to 230 and temperature were below 100°C. Based on steady state conditions, Galloway and Sage [10] developed a correlation for the gas to particle heat transfer coefficient for spherical pellets. Nasr et al [11] gave an experimental study of forced convection heat transfer from a cylinder in a packed bed of spherical particles. Aluminum, alumina, glass and nylon were used as packing materials. The operating fluid is air. The authors demonstrated that the uncertainly in the reported Nusselt numbers was ± 20 %. Balakrishnan and Pei [12] demonstrated that conduction between the particles in the bed and convection between the flowing gas and the particles which interact with each other, are the major reason for the difficulty in obtaining a single generalized experimental correlation or theoretical or semi-empirical models to evaluate the heat transfer coefficient in packed beds. Littman and Sliva [13] showed a strong dependence on Reynolds numbers especially for packed beds since the region near the point of contact between particles was not fully accessible to the flowing fluid. The heat transfer coefficient was also determined for agro alimentary products: Wang et al [14] and Bala [15] studied, experimentally, the convective heat transfer coefficient in packed bed of rice and malt, respectively. Khandker and Woods [16] measured the heat transfer coefficient in packed beds of barley. This coefficient was found to be a function of air flow rate. Most of the previous studies presented above required excessive instrumentation and time. Following this line of thinking, the present work aims to design, fabricate and assemble a 8 cm x 8 cm square cross section and 1.4 meter height packed bed. Also, the main parameters which affect in the heat transfer side as well as the bed conditions such as velocity of the air, particles size, and temperatures are measured.

2. Experimental Setup, Instrumentation and Procedure

2.1 Experimental set up

The experimental investigations were carried out in an open circuit, specially built and designed for the present research work. The experimental set up photographic view is shown in figure (1) which illustrates a general view of the individual components of the testing installation , creating a bed column of size (8 cm x 8 cm) . Figure (2) shows schematically the experimental setup with its components which basically consist of the following parts:-

- Hot air supply.
- Divergence section.
- Distributor plate.
- Test section.

2.1.1. Hot air Supply

The bed is supplied with air from an air heat gun with the following technical data:

Rated power input	2000 W
Rated voltage input	220 V
Frequency	50/60 Hz
Current consumption	9 A
Main switch	1, 2 and 3
Air flow rate	Up to 500 liter/min
Temperature	50 : 600 ^{o}C
Temperature adjustor	1:9
Weight	0.8 kg

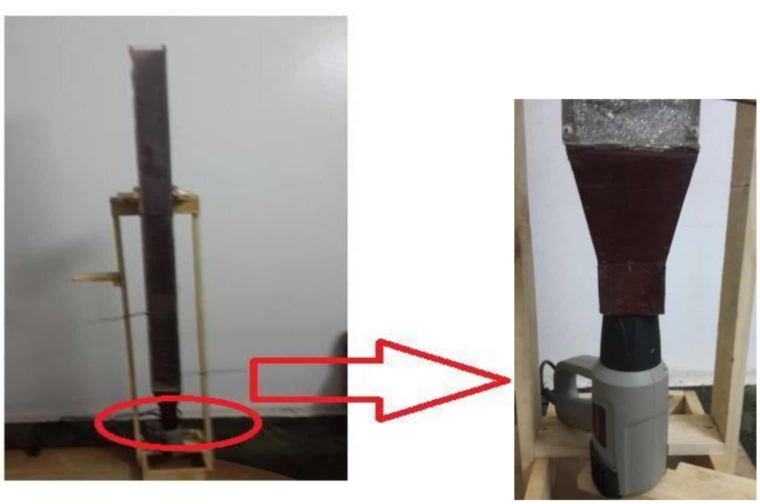

Figure (1): General view of the experimental setup

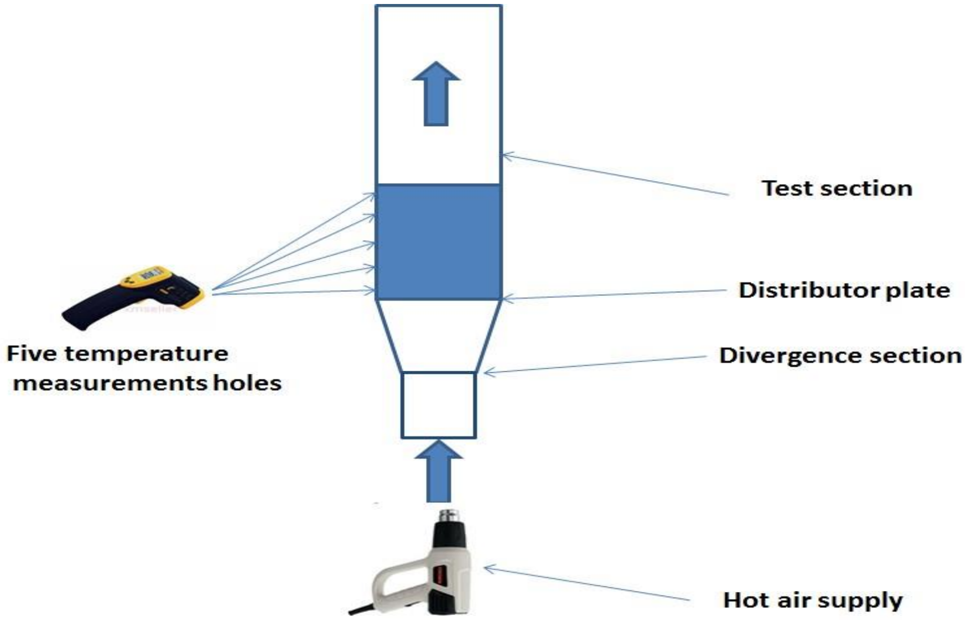

Figure (2) schematic diagram of the experimental setup

The inlet regulator at the heat gun inlet controlled the air flow rate. Air flows through the divergence section which makes the flow uniform at the inlet of the distributor plate.

2.1.2 Divergence section

Divergence section reduces the air flow velocity and makes the flow uniform at the inlet of the distributor .The divergence section is made of wood with thickness 2 cm.

2.1.3 Distributor Plate

The distributor plate may be considered as the most important component of the packed bed system. It plays a key role in maintaining a high degree of quality of flow necessary to make the system effective. It must make several functions. The most important of these functions are mentioned below: -

a. Weeping of the solid particles must be minimized.

b. It must induce uniform and stable fluidization across the bed.

c. Dead zones should be small as possible.

d. It should minimize the attrition of bed material also to prevent serious erosion of bed material.

e. It should be mechanically strong enough to with stand extreme conditions that it is subjected to.

Among the several types of distributor plates, a screen type is the simplest one. Five sheets of steel screen (0.4 X 0.4 mm) are used to support the weight of the bed.

2.1.4 The Test Section

he square test section column (8 cm x 8 cm) is designed and fabricated so as to facilitate performance of experiments pertaining to basic dynamic and in-bed heat transfer. The section is constructed out mainly of wood of thickness of 2 cm for three walls while the fourth wall is made of 18 mm thickness highly transparent Perspex. The section is kept quite tall enough for permitting deep bed experiments, where the length is 1.4 meter. Fig. (1) shows the actual view of the test section along with different dimensions. The Perspex window in the test section allows visual observation of the bed.

2.2 Instrumentation and Measurements

Instruments and calculations have been used to measure important parameters, temperature, air velocity, void fraction and diameter of particles. Instruments have been calibrated before start the investigation.

2.2.1 Temperature Measurement

Bed temperature is measured by using smart sensor laser infrared thermometer. Five holes are made in the side of test section as shown in figure (2) to measure the bed temperature at different levels. The smart sensor laser infrared thermometer smart has the following technical data:

- Measuring range : - 32 to 3000 ˚C
- Resolution : ± 2% of reading
- Accuracy : ± 2 ˚C
- Battery type : 2 x micro (AAA)

2.2.2 Velocity Calculation

Airflow velocity is calculated by dividing the volume flow rate outgoing from the air heat gun by the cross section area of the test section.

2.2.3 Particles Size measurement

Particles are not of the uniform sizes. Size distribution of the particles in the sample is found by calculation. A few amounts of particles is weighted by digital balance. By knowing of particles density the equivalent particles diameter can be found.

2.2.4 Void Fraction Measurement

The void fraction (porosity) is measured by the quick closing valve technique .In this method, valves (which can be quickly and simultaneously operated) are placed at the beginning and end of the section of channel over which the void fraction is to be determined. At the appropriate moment, the valves are actuated and the liquid phase trapped in the channel is drained and the volume measured. Since the channel volume is known (or can be estimated), the channel average voidfraction can be found.

2.3 Properties of Air and aluminum particles

2.3.1 Properties of aluminum particles

Density , ρ_s	2707 kg/m^3
Particles average diameters , d_P	5 mm
Bulk bed porosity , ε	0.42
Specific heat , C_{ps}	896 J/kg ˚C

2.3.2 Air Properties

Density , ρ_g	1.177 kg/m^3
Viscosity , μ_g	18.4 x 10^{-6} kg / m .s
Specific heat , C_{pg}	1005.7 J/kg ˚C
Thermal conductivity , k_g	0.0267 W/m ˚C
Prandtl number ,$Pr = \mu_g C_{pg} / k_g$	0.708

3. Computation of gas to particle heat transfer

The temperature of the particle surface that is necessary to quantify the heat transfer can be conveniently described in term of the gas to particle heat transfer coefficient. Based on experimental temperature measurements obtained in this work, a simple model was developed considering steady state energy balances and assuming:

1. The granular medium is homogeneous and isotropic.
2. The bed porosity is uniform.
3. The operation is adiabatic.
4. The bed is considered as a two-phase mixture (solid and gas) .

The packed bed is a discontinuous granular medium made of spherical porous particles (solid phase) crossed by hot air (gas phase). Energy balances are made in a bed portion whose height and cross section are respectively dH and S_0 as shown in figure (3).

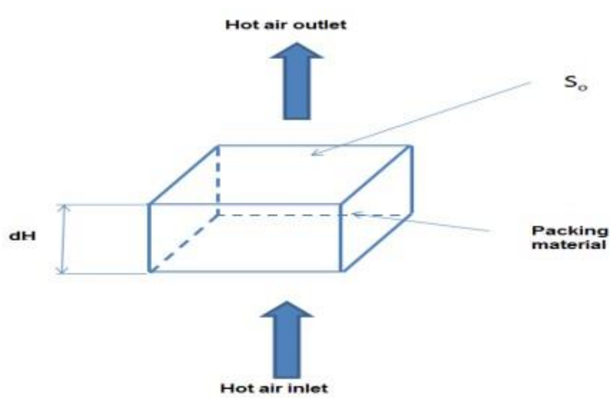

Figure (3): Packed bed section

The solid phase internal energy (I_s) is relayed to the mass of the bed (M_b) and the bed temperature T_b:

$$\frac{dI_s}{dt} = M_b C_{ps} \frac{dT_b}{dt} \qquad (1)$$

With C_{ps} , M_b and T_b are the particles specific heat , the bed mass and the bed temperature respectively.

From the energy balance:

$$\frac{dI_s}{dt} = h(T_g - T_b) S_b \qquad (2)$$

Where h and S_b are gas to particle heat transfer coefficient and is the total surface area of the particles respectively.

For spherical particles $S_b = \frac{6(1-\varepsilon) S_0 H}{d_p}$ (3)

Where ϵ, dp and H are the porosity, the particle diameter and the bed height respectively.

By substituting by equation (3) in equation (2):

$$\frac{dI_s}{dt} = h(T_g - T_s) \frac{6(1-\varepsilon) S_o H}{d_p} \qquad (4)$$

By substituting by equation (1) in equation (4):

$$M_b C_{ps} \frac{dT_b}{dt} = h(T_g - T_b) \frac{6(1-\varepsilon) S_o H}{d_p} \qquad (5)$$

Integration results on:

$$\ln\left(\frac{T_{bf} - T_g}{T_{bi} - T_g}\right) = -\frac{6h(1-\varepsilon) S_o H}{M_b C_{ps} d_p} t \qquad (6)$$

T_{bf} and T_{bi} are final and initial bed temperature respectively.

This equation indicates that a plot of the logarithmic temperature $\ln\left(\frac{T_{bf} - T_g}{T_{bi} - T_g}\right)$ versus time should present a straight line with a slope equal to $-\frac{6h(1-\varepsilon) S_o H}{M_b C_{ps} d_p}$. The value of h can be given from this slope.

4. FEHT setup

In this section the different steps to prepare FEHT code are declared. The model is a transient heat transfer analysis of a packed bed as shown in figure (4). The air enters upward through the bed at 50^{o}C. The surrounding air around the bed is at atmospheric conditions and 20^{o}C. The model is to determine the temperature distribution in the bed area and the temperature varying versus time. The two sides of the bed are insulated. The bed height , the initial temperature and the total simulation time iare taken 20 ^{o}C, 11cm, 1400 second respectively.

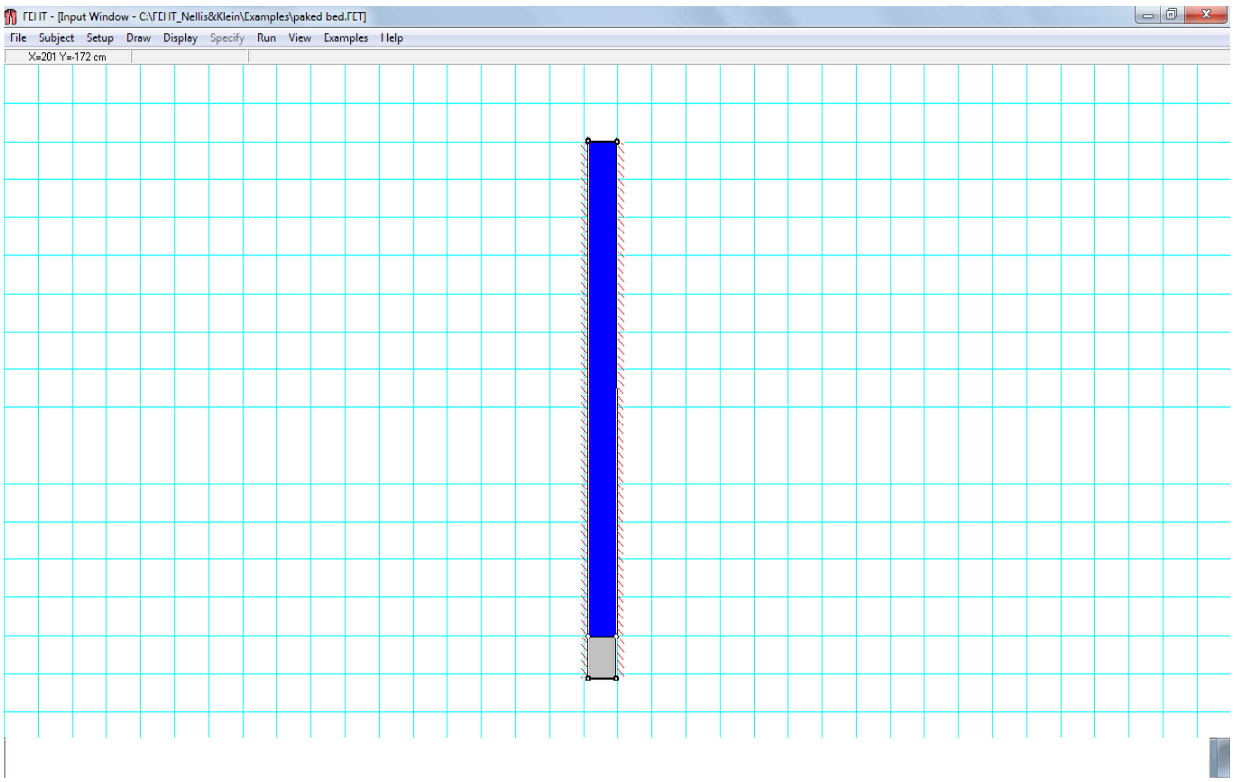

Figure (4) FEHT setup

5. Results and discussion

In the present work, the effect of Reynolds number on heat transfer was investigated. The packed bed material used in the present study was Aluminum of equivalent diameter of 5 mm.

The following sections report the results of the experimental program. Also the present work data is verified with the previous work data. Finally, a FEHT model was created and the present work data was compared with its output.

5.1 FEHT results analysis

Figure (5) shows the output results of FEHT. After prepare the required model to FEHT the output results of temperature contours are presented in figure (5). These results are in good agreement with the final results of the present work. Where the bed reaches the initial temperature of gas (50^{o}C) and the heat balance is occurred.

Figure (6) illustrates the relation between the time and the bed temperature for both FEHT and the present work. Although it cleared that the two curves have the same trend but the difference in time of reaching stable temperature is due to the code technique. These means that the code deals with the bed as a lumped material meanwhile the equivalent properties are given to the code.

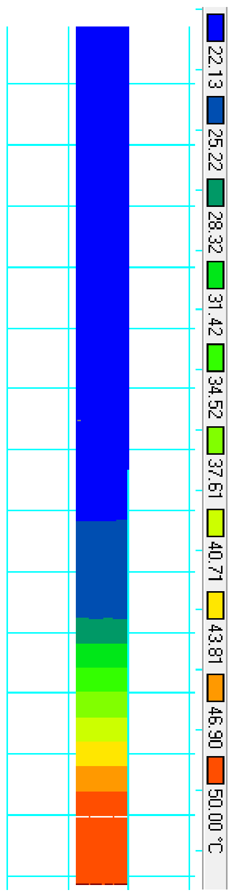

Figure (5): FEHT temperature contours results

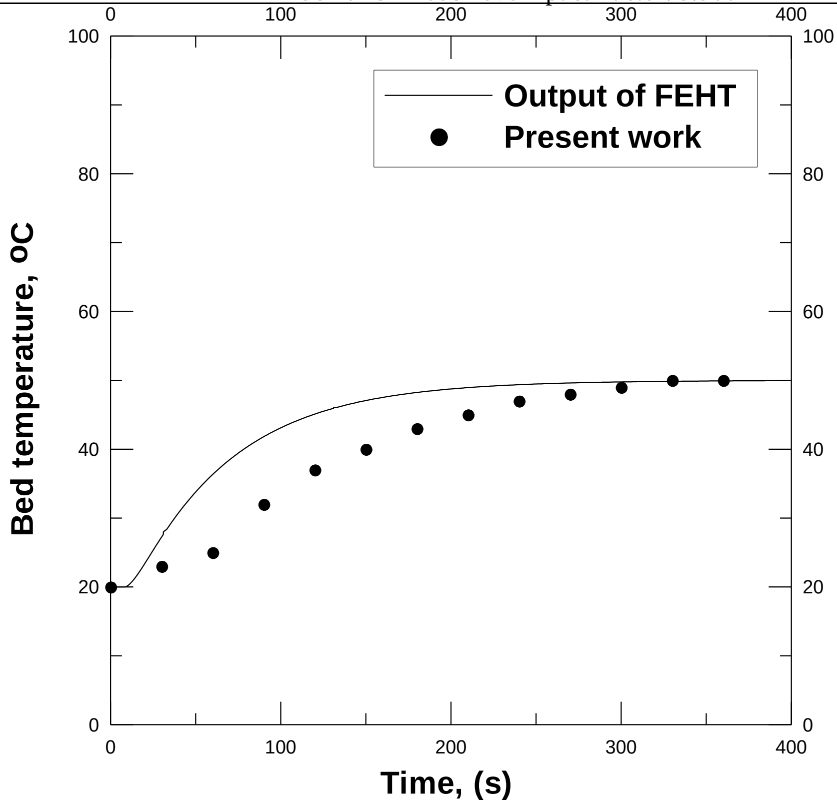

Figure (6): Comparison between FEHT results and Present work

5.2 Present work analysis

Figure (7) shows the variation of bed temperature with the time at gas velocity 0.9 m/s for different bed height (H=6 and 11 cm). Also figure (8) presents the variation of bed temperature with the time at the previous two bed heights but at velocity 1.3 m/s. The same results trends are observed in the two figures. The bed reaches the gas temperature more quickly at (H=6 cm) than (H=11 cm). These are logic results because with the increase in bed height the thermal capacity increased consequently more time is needed to reach the gas temperature.

Figure (9) shows an example of these logarithmic temperatures differences versus time for different values of gas velocity. As expected, a family of straight lines was produced. The determination of slopes of these lines leads to the measured heat transfer coefficient and consequently the experimental Nusselt number.

Figure (10) illustrates the relation between Nusselt and Reynolds numbers for the model developed in this study compared with correlations reported in the literature for packed bed of spherical porous alumina particles [1, 2]. It can be seen that a general correlation relating Nusselt with Reynolds for different materials with a wide range of physical and transport properties is not possible. This has been generally observed in the literature where the correlation for the heat transfer coefficient of one author working with one materiel is often at variance with that of other author working with some other materials. In fact, the heat transfer coefficient is dependent both on the thermal properties of the bed and on the flux rate.

However, most experimental correlations express it as a function of the Reynolds number. Therefore, the applicability of these correlations is also limited to the particular bed materials used in developing them. Moreover, the thermal properties of the walls (adiabatic or heated) have a significant effect on the conduction mode and therefore studies using similar experimental techniques but different bed materials can also be expected to yield different correlation relating the heat transfer coefficient to Reynolds numbers. As explained above, discrepancies in Nusselt number were found. This may be due, also, to some differences in experimental conditions (particles characteristics, height and diameter of the packed bed, boundary conditions...). These

discrepancies can be also attributed also to the position of the thermocouples and errors in the measurement.

For these reasons, a simple model based on experimental measurements allowing the calculation of heat transfer coefficient for each packed bed material with moderate experimental instrumentations is developed in the present work

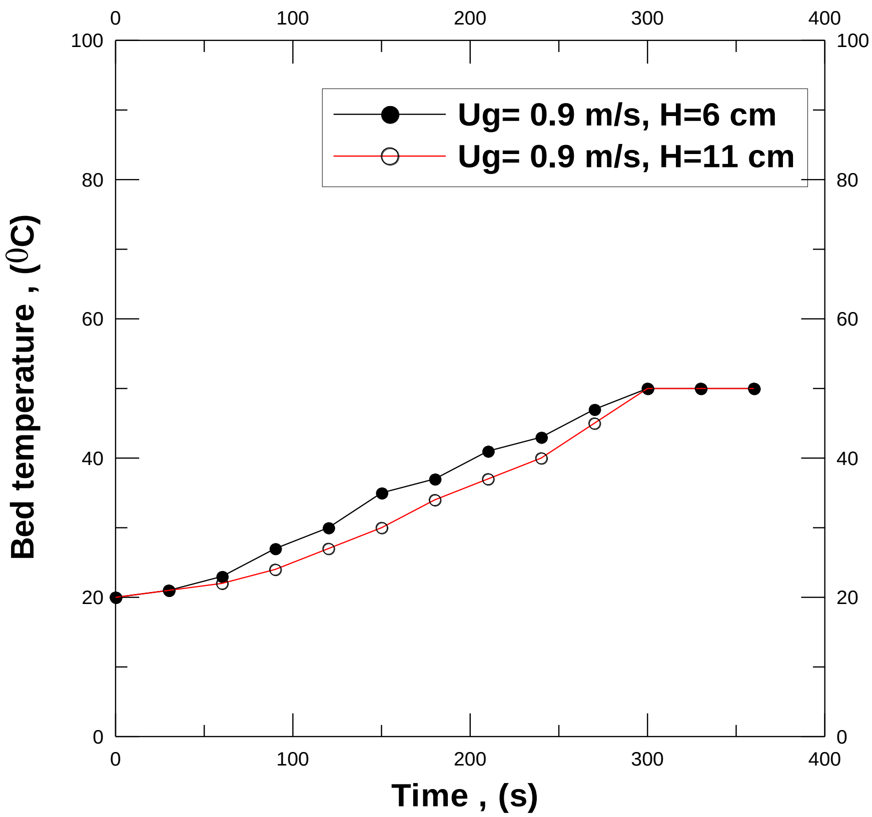

Figure (7): Variation of bed temperature with time at U_g=0.9 m/s

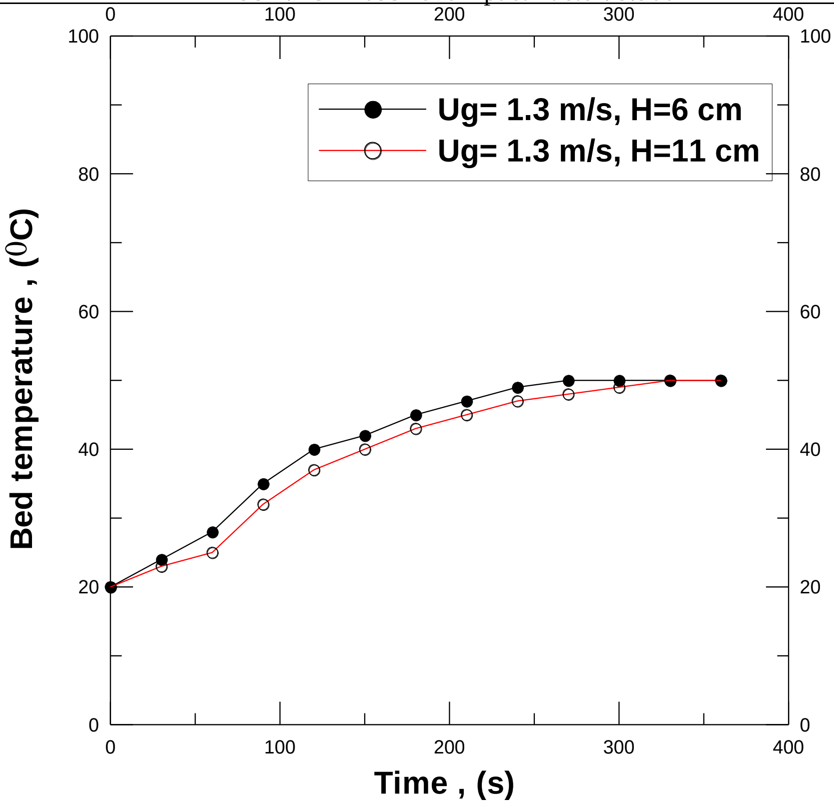

Figure (8): : Variation of bed temperature with time at U_g=1.3 m/s

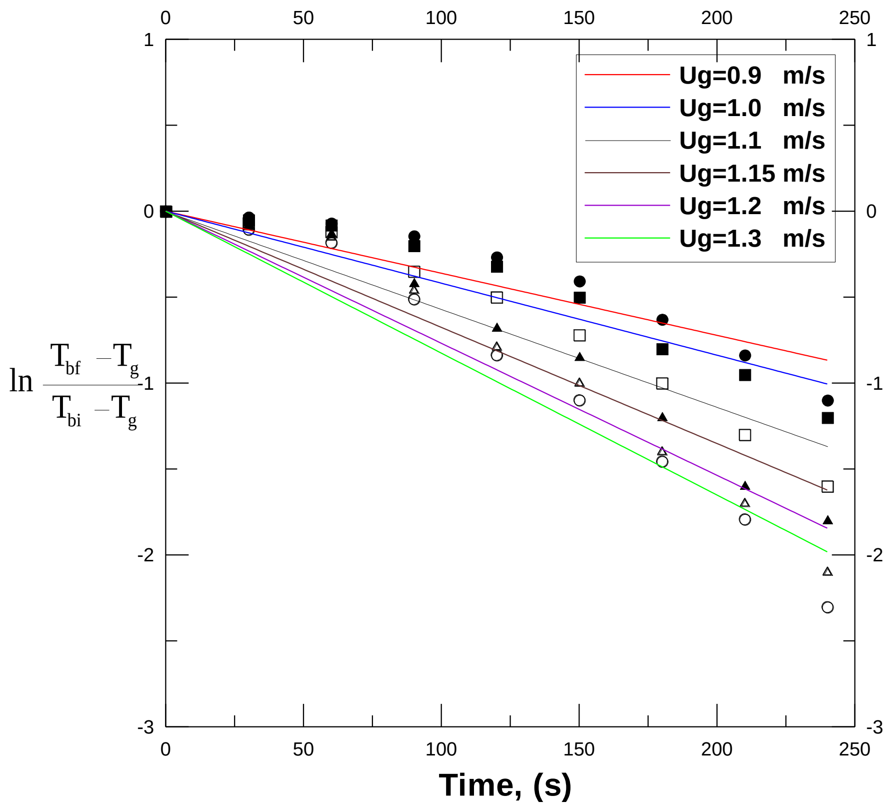

Figure (9): Straight lines obtained from equation (5-6)

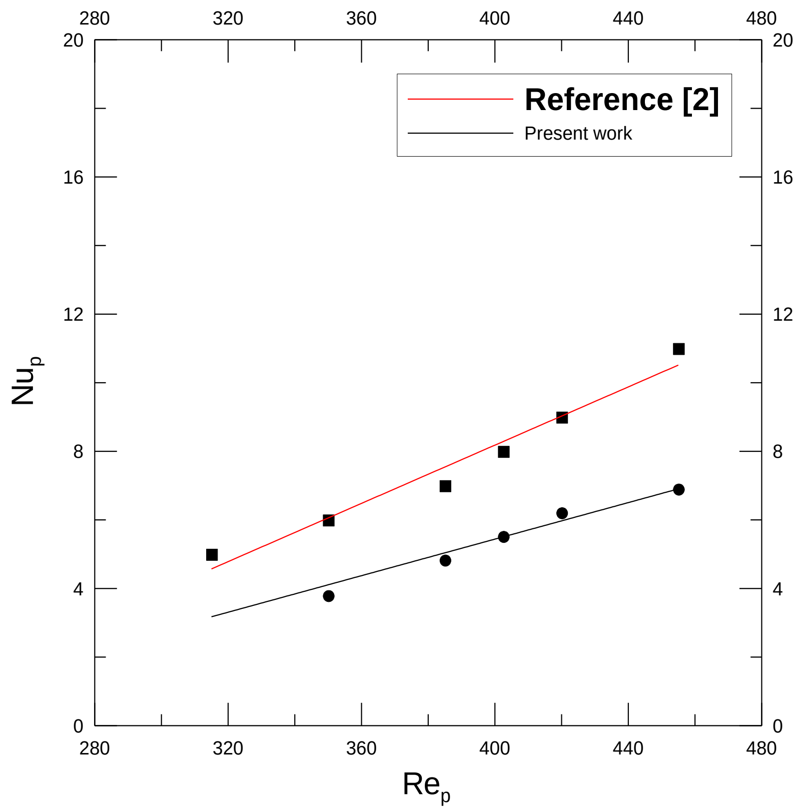

Figure (10): Comparison between Nusselt and Reynolds numbers for present work and Reference[2] at the same conditions

6. Conclusions

The present work aims to study the heat transfer characteristics between packed bed and gas pass upward through the bed. The results of the investigation may be briefly summarized as:

1. The gas velocity has a great effect in the mechanism of heat transfer. The heat transfer coefficient increases with the increase of the air velocity.

2. The increase of the bed total head increase the time required to reach the thermal balance conditions.

3. The present work shows a reasonable agreement with the previous work.

4. FEHT Results are compatible with the present work results.

Nomenclature and Abbreviation

Symbol	Definition	Dimensions
C_p	Specific heat at constant pressure	J/kg.K
d_p	Mean particle diameter	m
g	Acceleration due to gravity	m/s^2
FEHT	Finite Element Heat Transfer program	
h	heat transfer coefficient between gas phase and particle phase	$W/m^2.K$
H	Total height of the bed and freeboard	m
I	Internal energy	J
K	Thermal conductivity	W/m.K
M	Mass	kg
P	Pressure	Pa
U	Superficial gas velocity	m/s
S_o	Cross section area of test section	m^2
S_b	total surface area of the particles	m^2
t	Time	S
T	Temperature	$^{\circ}C$

Dimensionless Groups

Nu	Nusselt number based on particle diameter, $Nu_p = h\, d_p/k_g$
Pr	Prandtl number , $Pr = \mu_g C_{p,g}/k_g$
Re	Reynolds number based on particle diameter , $Re_p = d_p \rho_g U_g/\mu_g$

Greek Letters

ΔP	Total Pressure drop across the bed	Pa
$\in$	Volume fraction	--
ρ	Density	Kg/m^3
μ	Viscosity	Pa.s

Subscript

G Gas phase

s Particle phase

B Bed

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