EFFECTIVE HEAT TRANSFER PARAMETERS IN BEDS PACKED WITH SPHERICAL PARTICLES

T.E. Farrag, M.M. Nassar, O.A. Fadali and E.A. Ashour
Chemical Engineering Department, Faculty of Engineering, Minia University, El-Minia, Egypt.

ABSTRACT:

Effective radial thermal conductivity and wall heat transfer coefficient for packed bed of non reacted material, 4.8mm alumina spheres, were experimentally determined at high temperatures up to 850 ºC for flow rates giving particle Reynolds numbers in the range of 10 - 220. Radial temperature profiles were measured at various axial positions. The results were analysed on the basis of a two-dimensional pseudohomogeneous non-plug flow model, where velocity profile take into account. Over these ranges both parameters, λ_{er} and α_w, showed significant dependence on gas flow rates for all different wall temperatures and these dependencies were predicted well by correlations with particle Reynolds number.

INTRODUCTION:

The catalytic reaction of gases forms the basis of many important industrial processes. Most of these reactions are carried out in fixed bed reactors. Therefore, packed beds of gas-solid systems have a central place as a processing tool in chemical engineering operations. Their inherent characteristics of extended fluid interfacial area and good fluid mixing have led to its application in a wide variety of physical and chemical processes. These include chemical reactors, drying, distillation, gas adsorption, absorption, regenerators, thermal insulations, grain storage, solid matrix heat exchangers, oil extraction and manufacturing of cement bricks. Many of these processes involve the transfer of heat between the bed material and the fluid. The process design of such systems requires a knowledge of the heat transfer characteristics of the bed at the process temperatures, gas velocity, bed structure, properties of fluid, properties of solid, bed voidage, packing characteristics and the reactor tube itself.

Heat transfer behavior of fluid flow through packed tube and channel has an important impact on the design and operation of catalytic reactors. McGreavy et al. (1986) emphasized how the accuracy of the heat transfer parameters can effect the predicted temperature distributions of reactors by utilizing two sets of correlations to predict wall heat transfer coefficient, α_w, and effective radial thermal conductivity, λ_{er}. These effective transport parameters reflect the increased thermal resistance in the vicinity of the wall. The ratio of tube to particle diameter, d_t/d_p, is directly related to the properties of the wall region especially for the gas phase system due to increase in porosity, Dixon (1985 & 1997).

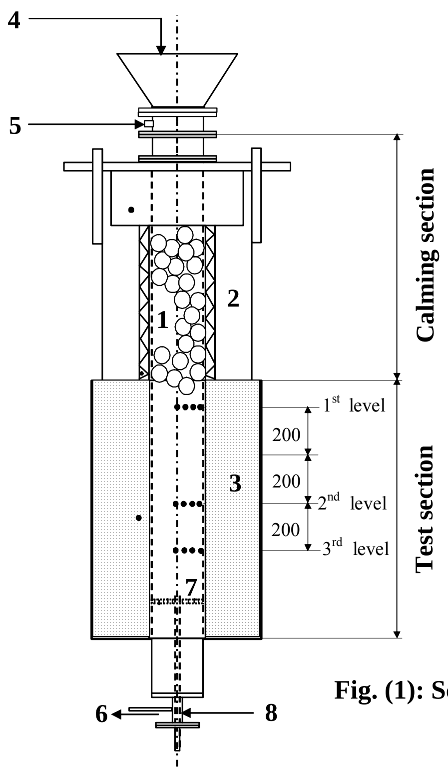
It has been difficult to obtain satisfactory correlations of heat transfer coefficients for packed beds with small values of d_t/d_p. Dixon (1985 & 1997) studied the region $5< d_t/d_p<12$ and $d_t/d_p<4$, while De-Wasch and Froment (1972) studied the region $7< d_t/d_p<27$, and they determined the parameters for various size and shape of packing and pointed out that the mixing phenomena on a particle scale may play an important role in the process of radial heat transfer. Tsotsas and Schlunder (1990) associated the heat transfer coefficient with the spatial extent of the wall region with respect to tube diameter. The procedure of Coberly and Marshall (1951) for determining the effective transport parameters from the spatial distribution of fluid temperature has been widely used, Tsotsas and Schlunder (1990). Although, it has been a common practice to correlate α_w and λ_{er} in terms of a Reynolds number based on the particle diameter d_p, there has been no general agreement on the form of the correlations for the packed beds. The wall Nusselt, Nu_w, is expressed in a linear form, Yagi and Kunii (1960), De-Wasch and Froment (1972) and Dixon (1997), as well as in an exponential form, Li and Finlayson (1977) Borkink and Westerterp (1994) and Demirel, et al. (1999) with respect to Reynolds number Re_p. The correlations of λ_{er}/λ_f are mainly expressed in a linear form with respect to Re_p, Dixon (1985, 1997), Borkink, Westerterp (1992) and Demirel, et al. (2000).

Most of previous studies in field of heat transfer in packed bed systems were carried out using inert materials. The studies have been done in a wide range of Reynolds number for different materials with different shapes and sizes. The different operating conditions which were studied covered, constant wall temperature and constant heat flux, with different packed tube design. Usually the heating medium was steam, by using steam jacket, since the range of temperature which has been studied is small. However, one of the dependence of effective radial thermal conductivity for packed systems with gas flow is the properties of both packing material and the fluid flow where, both of them are directly affected by the temperature. The aim of this study is to investigate the above mentioned parameter in a wide range of bed temperature up-to 850 ºC. This temperature range is very important in stat of chemical processes such as pyrolysis and gasification of biomass. In this investigation, effective radial thermal conductivity and wall heat transfer coefficient have been determined for a bed packed with 4.8 mm particle diameter alumina sphere at different air flow rates to achieve different particle

Reynolds number up-to 220. The measurements were carried out at different wall temperatures (100 : 850 ºC). The predicted parameters were correlated in an empirical correlations as a function of particle Reynolds number.

EXPERIMENTAL APPARATUS AND PROCEDURES:

A schematic diagram of packed bed used in this study is shown in Fig. (1). The unit consists of a steel tube, 2000 mm length, 82.5 mm inner diameter and 89.0 mm outer diameter. The lower part of the tube is surrounded by tube oven electrically heated to a maximum temperature 1100°C. The lower part of the tube is the test section and the upper part plays the role of calming section, which was filled by identical packing materials. Near the bottom of the tube, there is a steel grid to support the packing materials in both sections. A down wards flowing cold fluid (air) approximately at room temperature is heated up in the tube. Air supplied from the laboratory high pressure line. The air flow rate is adjusted by using rotameters and measured at the end of the bed by a gas-meter as an accurate way for measuring volumetric flow. Temperature and pressure of the fluid are also measured. From these three values, mass flow is easily calculated.



1- Packed bed
2- Insulation
3- Electric Oven
4- Gas input
5- Gas input
6- Gas out put to flow measuring unit
7- Steel screen
8- Thermocouple for gas output
● Thermocouples positions
note: all dimensions in mm

Fig. (1): Schematic diagram of packed bed tube and positions of temperature measurements.

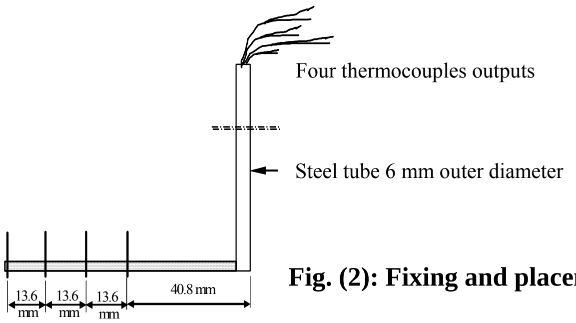


Fig. (2): Fixing and placement of thermocouple for each level.

The packed tube was equipped with 14 thermocouples, type *K* of 1 mm diameter. One thermocouple measured the inlet temperature of the air and another one measured outlet temperature at the end of the tube. 12 thermocouples were radialy distributed in three axial levels. These are distributed as four thermocouples for each level. In each level, the distribution is as follows, one in centerline, one near the wall and two in between, to form the following ratios of r/R, 0.0, 0.33, 0.66 and 0.98. Thermocouples in first level were radialy distributed at the starting of heating in the packed tube to indicate inlet temperature profile of the fluid to test section. The second and third levels after 400 and 600 mm respectively from first level. Therefore, from this distribution, 12 measuring temperature points in radial direction in three levels are present. All measuring points are indicated by black dots in Fig. (1).

Because the test section stay inside the oven tube, so it is impossible to fix any thermocouple through the surface of the packed tube. The four thermocouples for each level are guided in a steel tube with 6 mm outer diameter connected in a steel flange at the top of the packed tube. The end of the steel tube is connected with a steel grid to form L shape. The thermocouples are fixed through holes in the grid at specified radial position r/R as shown in Fig. (2). The tips of thermocouples protruded from the grids about 10 mm to avoid any effect of the metal on the measuring values.

Alumina spheres was used as packed materials in this investigation where, it was provided from **Alcoa Industrial Chemicals, LLC in USA** with the following composition as weight percents, 93.1 Al_2O_3, 0.02 SiO_2, 0.02 Fe_2O_3, 0.30 Na_2O and 6.5 LOI (250-1100 °C). After the tube was filled with alumina, the oven was switched on to rise the temperature of the bed to a desired value. A data acquisition read and recorder all measured values at regular small intervals, three seconds was taken in this work, and monitored them in graphs with time. The bed was then allowed to reach steady state which took 8-10 hours depending on fluid flow rate, heating rate and the desired maximum wall temperature (end point). At steady stat, the measured values were used to determine the parameters by fitting it with specified model.

HEAT TRANSFER MODEL:

The system studied is a cold gas heated up in a wall heated cylindrical packed bed. Under the steady state conditions, the temperature field in cylindrical system is normally described by a two-dimensional pseudohomogeneous model, where the gas and bed temperatures are the same. The radial transport of heat through the bed is represented by an effective radial conductivity λ_{er}, and the experimentally-observed step increase in temperature near the wall is lumped into a temperature jump at the wall and described by an apparent wall heat transfer coefficient α_w. The temperature jump near the wall tended to one of assumption that the superficial velocity is not constant over the radius of the bed but it has a profile calculated in this study according to Vortmeyer and Schuster (1983).

The axial dispersion was neglected compared with the convection term. From all these assumption, the temperature equation becomes, non-plug flow two-dimensional pseudohomogeneous without axial dispersion model and written as follow,

$$\frac{\partial \theta}{\partial y} = \frac{d_p L}{Pe_r R^2} \frac{\overline{u}_0}{u_0(\xi)} \left[\frac{\partial^2 \theta}{\partial \xi^2} + \frac{1}{\xi} \frac{\partial \theta}{\partial \xi} \right] \tag{1}$$

with the boundary conditions,

$$\theta = \theta_{in}(\xi) \;, \qquad at \quad y = 0$$

$$\frac{\partial \theta}{\partial \xi} = 0 \;, \qquad at \quad \xi = 0$$

$$\frac{\partial \theta}{\partial \xi} = Bi(1 - \theta), \qquad at \quad \xi = 1$$

The parameters were determined by the method of least squares, where its values were adjusted by search so that the model predicted dimensionless radial bed temperature close to the observed steady state temperatures for two different axial bed lengths. The least square estimation minimized the sum of the squares of the discrepancies between observed and predicted temperatures. Thus for a total number of readings, the best fit was obtained by finding the minimum value of deviation using the following correlation,

$$\in = \sum_{i=1}^{m} \left(dev(i) \right)^2 = \sum_{i=1}^{m} \left[\theta_{obs,i} - \theta_{calc,i} \right]^2$$

Where, m is the number of measured points in the whole test section.

RESULTS AND DISCUSSIONS:

1- Effective radial thermal conductivity:

Effective radial thermal conductivity for mono-sized alumina spheres, in a cylindrical packed bed heated at the wall was predicted by fitting the temperature profiles measurements with the suggested model. This parameter is obtained at different conditions for wall temperature and fluid flow rates. The wall temperatures which are used in the experiments are 100, 150, 300, 500, 700 and 850 ºC with air flow rates 17.83, 33.15, 55.75, 77.54, 100.98 and 126 l/min. to cover range of particle Reynolds number from 10 to 220. The results are shown graphically in Figs.(3 to 8) which is a plot of effective radial thermal conductivity versus particle Reynolds number for each appropriate wall temperature, where it appears that the effective radial thermal conductivity increase with increasing Reynolds number. The effective radial thermal conductivity changes with Reynolds number by a linear function. This finding is in agreement with the most results in literatures i.e., Yagi and Kunii (1957 & 1960), Yagi and Wakao (1959), Kunii and Smith (1960), Dixon (1985 & 1997)), De-Fasch and Froment (1972), Chalbi et. al. (1987), Freiwald (1991), Tsotsas (1997) and Demiral et. al. (2000). From the plots it is appears that, the dependence of effective radial thermal conductivity on the bed height is much smaller in magnitude at low temperatures and the dependence disappeared at high temperatures. The smallest dependence on the bed length tend to lower thermal conductivity of the packed material also may be due to heat conduction to the calming section through the tube wall and the holder tube of thermocouples. From this conclusion, the length effect may not have a significant and both data of the two bed lengths are taken together to fit the parameters with Reynolds number.

Due to the effect of temperature on the thermal properties of both solid particles and fluid flowing through the bed and also due to the fact that heat transfer by radiation mechanism is largely affected by temperature so, the whole bed properties are also affected by temperature. The data are shown graphically in Fig. (9) which is a plot of effective radial thermal conductivity versus the mean values of bed temperatures for different values of particle Reynolds number. The thermal conductivity was found to increase with increasing bed temperature. This is entirely consistent with the nature of both solid material and the fluid used. From the plot it is clear that, the change of effective radial thermal conductivity with temperature is increased at high bed temperature $T > 350$ ºC specially with the high gas flow. This is due to the contribution of both convection and radiation to the effective thermal conductivity according to the following equation,

$$\lambda_{e,r} = (\lambda_{e,r})_{cond} + (\lambda_{e,r})_{conv} + (\lambda_{e,r})_{rad} \qquad (2)$$

An empirical equation was sought to fit the measured data and to relate the dimensionless effective radial thermal conductivity to both stagnant bed thermal conductivity (conduction term) and Reynolds number (convection term). The predicted equation was found to be,

$$\frac{\lambda_{e,r}}{\lambda_f} = \frac{\lambda_e^{o}}{\lambda_f} + 0.03 Pr.Re_p \qquad (3)$$

Where this correlation is valid at $d_t/d_p = 17.2$ and $10 \le Re_p \le 220$

The predicted correlation has a form similar to most correlations in literatures, where most empirical correlations in literatures were presented in a general form as follow,

$$\frac{\lambda_{e,r}}{\lambda_f} = \frac{\lambda_e^{o}}{\lambda_f} + f Pr.Re_p \qquad (4)$$

A comparison between measured values of effective radial thermal conductivity and its values predicted by equation (3) are plotted in Fig. (10). From this figure, all values approximately fall on the 45º line for different bed temperatures and fluid flow. This means that, the measured and predicted values are in a good agreement. Also the percent of mean deviation between measured and predicted values was calculated and it was found that, it is ranged between ±8 %.

Effective radial thermal conductivities predicted by equation (3) are compared with other data in literature, Yagi and Kunii (1957), Freiwald (1991), Dixon (1997) and Tsotsas (1997). All correlations as well as predicted equation have a linear form with same intercept equal to λ_e^o / λ_f and different slops so, the differences are only in the convection term. From the plots it appears that the deviation between the correlations of different literatures is only in the expression of (*f* factor). This deviation is due to difference of models used in the analysis of measurements. Fig. (11) shows a comparison between predicted values with different models for wall temperature 300 ºC. From this figure it is clear that the obtained correlation is in good agreement with data predicted by Freiwald (1991) and Tsotsas (1997) than others specially at high temperatures because similarity of data analysis. The deviation is tended to also that, the same model was used by the first one but without taking the effect of porosity and velocity distribution in his account while the second one toke it in his analysis.

2- Wall heat transfer coefficient:

Wall heat transfer coefficient α_w is evaluated as a second parameter with effective radial thermal conductivity $\lambda_{e,r}$ to give a deep understanding of heat transfer in packed bed systems. Wall heat transfer coefficients were estimated according to the definition:

$$\alpha_w = \frac{Bi.\lambda_{e,r}}{R} \qquad (5)$$

Where Biot number, Bi, is an expected value used in the numerical solution of the model. The estimated values are shown graphically in Figs. (12 & 13), where it was plotted versus particle Reynolds number for different wall temperatures and two bed lengths (L2 = 400 mm & L3 = 600 mm). Again, a linear relation is found with particle Reynolds number like the effective radial thermal conductivity. From these figures it is clear that, the dependence of the wall heat transfer coefficient α_w on bed height is very weak as in $\lambda_{e,r}$ and a typical case is shown in Fig. (14). The values of α_w are scattered and any variation with bed height is not significant compared with this scatter. Thus, the data are taken together without any dependence on bed height to fit the data in a correlation. The best fit values for the wall heat transfer coefficient are given in figures by a bold line and this changes is describe by the following form,

$$\alpha_w = \alpha_{w0} + f(Re_p.Pr) \qquad (6)$$

In literature, the wall heat transfer coefficient, α_w for a packed bed is often correlated as a power function with gas flow rate, in analogy to the heat transfer coefficient for an empty tube, Gunn and Khalid (1975), Li and Finlayson (1977) and Gunn et.al. (1987). For the present data, the relation is a linear function with particle Reynolds number, as was also found by Yagi and Kunii (1960), De- wash and Froment (1972), Chalbi et. al. (1987), Dixon (1985) and Tsotsas (1997).

Effect of bed temperature on α_w is shown graphically in Fig. (14) where, α_w was plotted versus wall temperature, for different mass flow rates of air. From plots it is clear that wall heat transfer coefficient has a proportional relation with wall temperature.

CONCLUSIONS:

From the experimental data and the discussions of results obtained through this study, it can be concluded that:

- Effective radial thermal conductivity and wall heat transfer coefficient were found to be linearly proportional with particle Reynolds number.
- The dependence of effective radial thermal conductivity on the bed height is much smaller in magnitude at low bed temperature and the differences disappeared at high bed temperature, so the bed height effect has no significant effect.
- The smallest dependence of heat transfer parameters ($\lambda_{e,r}$ & α_w) on the bed height is due to the lower thermal conductivity of packing material and also may be due to heat conduction to calming section through the tube wall as well as the probe of thermocouples.
- The effective radial thermal conductivity for a bed packed with alumina spheres with d_t/d_p=17.2 has been correlated in two terms, one depends on

stagnant thermal conductivity of the bed (conduction term) and the second depends on particle Reynolds number (convection term) as,

$$\frac{\lambda_{e,r}}{\lambda_f} = \frac{\lambda_e^o}{\lambda_f} + 0.03 Pr.Re_p \quad , \qquad 10 \le \mathrm{Re_p} \le 220$$

NOMENCLATURE:

Bi Biot number $(\alpha_w R / \lambda_{e,r})$

d_p Particle diameter, m

L Bed length, m

Pe_r Radial Peclet number $(\bar{u}_0 \rho_f Cp_f d_p / \lambda_{e,r})$

Pr Prandtl number $(\mu_f Cp_f / \lambda_f)$

r radial coordinate

R Tube radius, m

Re_p Reynolds number $(u d_p / \nu_f)$

T Temperature, ^{o}C, K

u_o Local Superficial velocity in empty tube, m/s

$\bar{u}_o$ Average Superficial velocity in empty tube, m/s

y Axial coordinate (z / L)

z Axial coordinate

Greek symbols:

α_w Wall heat transfer coefficient, W/m^2K

α_{wo} Stagnant contribution to α_w, W/m^2K

Є Standard deviation

λ_e^o Effective thermal conductivity without fluid flow, W/mK

$\lambda_{e,r}$ Effective radial thermal conductivity, W/mK

λ_f Fluid radial thermal conductivity, W/mK

μ_f Dynamic viscosity of the fluid, kg/ms

ρ_f Density of the fluid kg/m^3

υ_f Kinematic viscosity of the fluid, m^2/s

θ Temperature in test section $(T - T_o / T_w - T_o)$

ξ Radial coordinate (r / R)

Subscript:

calc Calculated

cond. Conduction contribution

conv Convection contribution

obs Observed

rad. Radiation contribution

w Wall

REFERENCES:

1. Chalbi, M., Castro, J. A., Rodrigues, A. E. and Zoulallan, A.; "Heat transfer parameters in fixed bed exchangers", Chem. Eng. J., 34, 89-97 (1987).
2. Coberly, C. A. and Marshall, W. R.; "Temperature gradients in gas streams flowing through fixed granular beds", Chem. Eng. Prog., 47, 141, (1951).
3. Demirel, Y., Abu-Al-Saud, B. A., Al-Ali, H. H. and Makkawi, Y.; "Packing size and shape effect on forced convection in large rectangular packed ducts with asymmetric heating", Int. J. Heat and Mass Transfer 42, 3267-3277 (1999).
4. Demirel, Y., Sharma, R. N. and Al-Ali, H. H.; "On the effective heat transfer parameters in a packed bed", Int. J. Heat and Mass Transfer 43, 327-332, (2000).
5. De-Wasch, A. P. and Froment, G. F.; "Heat transfer in packed bed", Chem. Eng. Sci., 27, 567, (1972).
6. Dixon A. G.; "Heat transfer in fixed beds at very low (< 4) tube to particle diameter ratio", Ind. Chem. Eng., 36, 3053 – 3064 (1997).
7. Dixon A. G.; "The length effect on packed bed effective heat transfer parameters", Chem. Eng. J., 31, 163, (1985).
8. Freiwald, M. G.; "Transport processes in packed beds of low tube to particle diameter ratio", Ph.D. thesis, university of Cambridge, UK (1991).
9. Gunn, D. J., Ahmad, M. M. and Sabri, M. N.; "Radial heat transfer to fixed beds of particles", Chem. Engng. Sci. 42, 2163-2171, (1987).
10. Gunn, D. J., and Khalid, M.; "Thermal dispersion and wall heat transfer in packed beds", Chem. Eng. Sci., 30, 261, (1975).
11. Li, C. H. and Finlazson, B. A.; "Heat transfer in packed beds- a reevaluation", Chem. Eng. Sci. 32,1055, (1977).

12. Li, C. H. and Finlazson, B. A.; "Heat transfer in packed beds- a reevaluation", Chem. Eng. Sci. 32,1055, (1977).
13. Tsotsas, E. and Schlünder, E. U., "Heat transfer in packed bed with flow: Remarks on the meaning and the calculation of a heat transfer coefficient at the wall"; Chem. Eng. Sci., 45, 819, (1990).
14. Tsotsas, E.; "Wärmeleitung und dispersion in durchströmten Schüttungen"; VDI- Wärmeatlas, Düsseldorf, Chapter Mh (1997).
15. Vortmyer, D. and Schuster, J.; "Evaluation of steady flow profiles in rectangular and circular packed beds by a variational method", Chem. Eng, Sci. 38, 1696-1699, (1983).
16. Yagi, S. and Kunii, D.; "Studies of effective thermal conductivities in packed beds"; AIChE J., 3, 373, (1957).
17. Yagi, S. and Kunii, D.; "Studies on heat transfer near wall surface in packed beds"; AIChE J., 6, 67, (1960).
18. Yagi, S. and Wakao, N.; "Heat and mass transfer from wall to fluid in packed beds"; AIChE J., 5, 79, (1959).

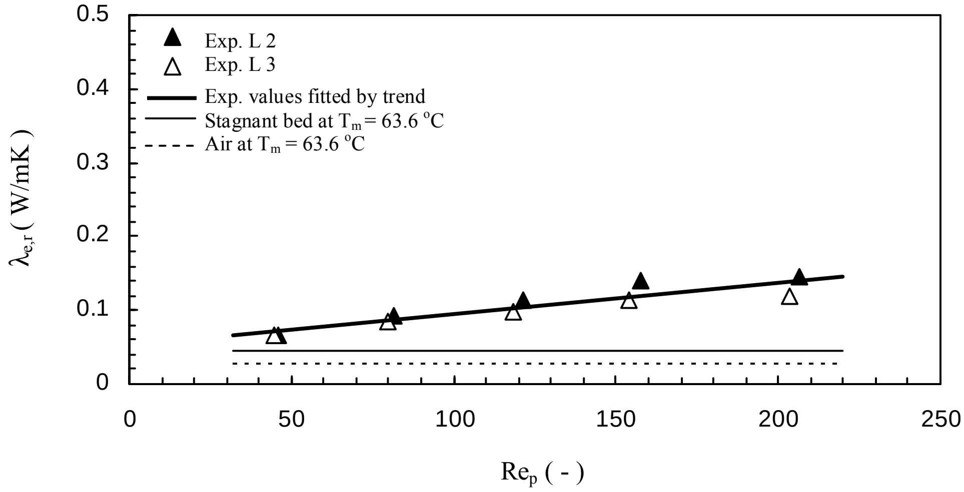


Fig. (3): Change of effective radial thermal conductivity for cylinderical packed bed of alumina spheres with particle Reynolds number , wall temperature 100 °C

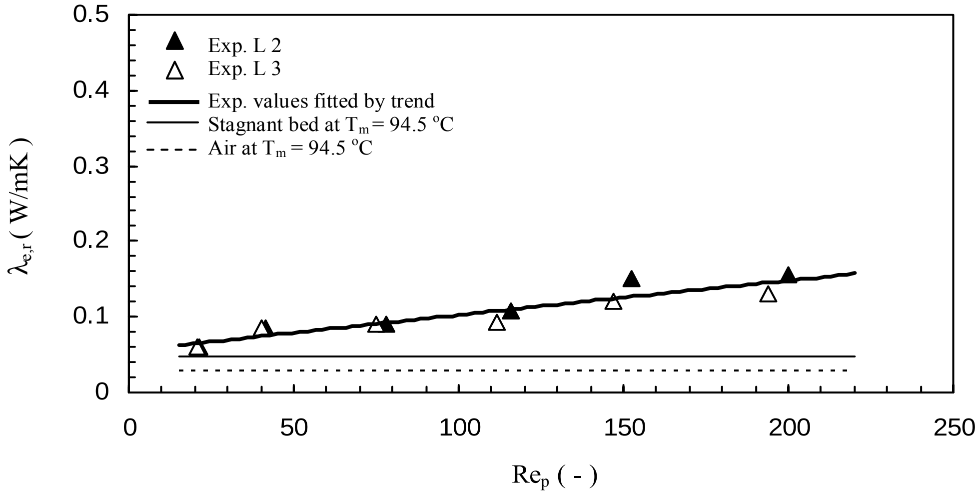


Fig. (4): Change of effective radial thermal conductivity for cylinderical packed bed of alumina spheres with particle Reynolds number , wall temperature 150 °C

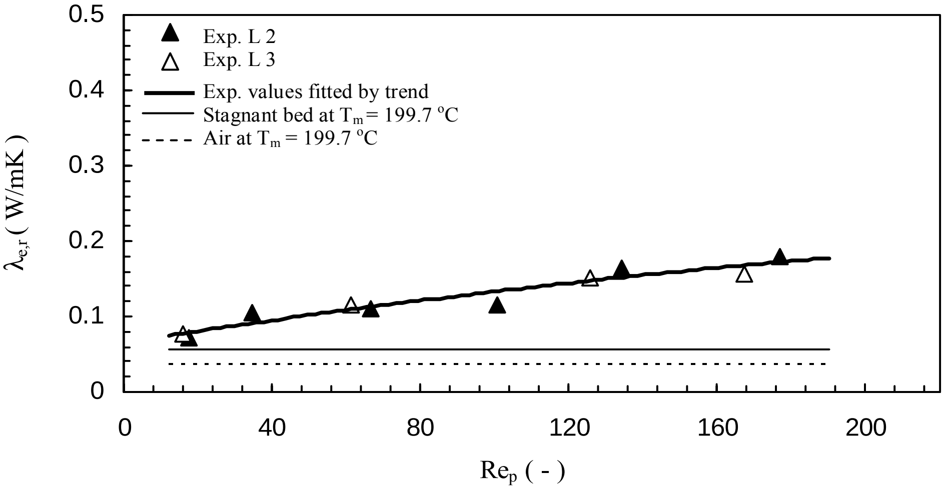


Fig. (5): Change of effective radial thermal conductivity for cylinderical packed bed of alumina spheres with particle Reynolds number , wall temperature 300 °C

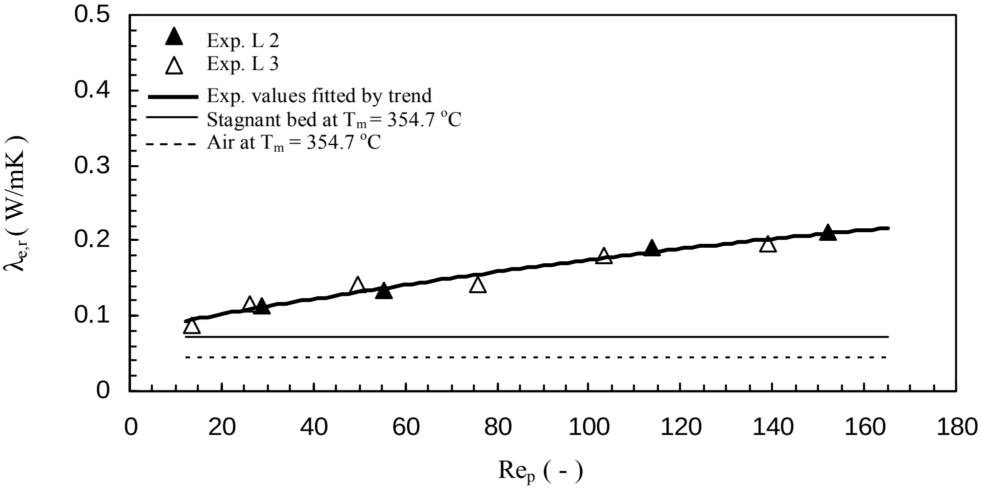


Fig. (6): Change of effective radial thermal conductivity for cylinderical packed bed of alumina spheres with particle Reynolds number , wall temperature 500 °C

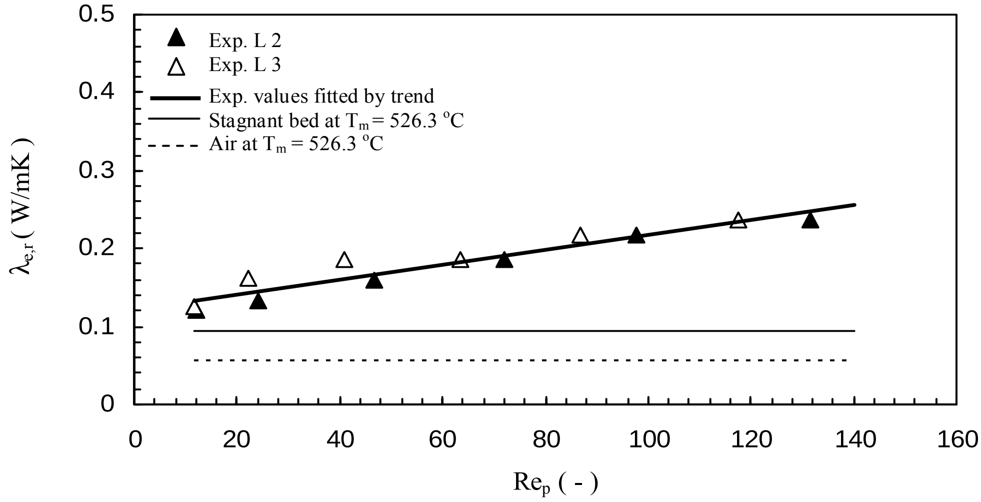


Fig. (7): Change of effective radial thermal conductivity for cylinderical packed bed of alumina spheres with particle Reynolds number , wall temperature 700 °C

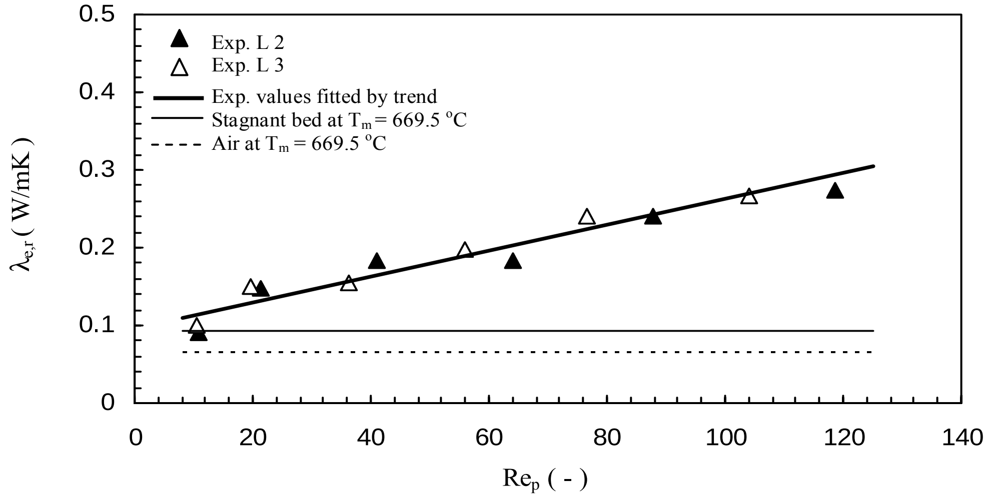


Fig. (8): Change of effective radial thermal conductivity for cylinderical packed bed of alumina spheres with particle Reynolds number , wall temperature 850 °C

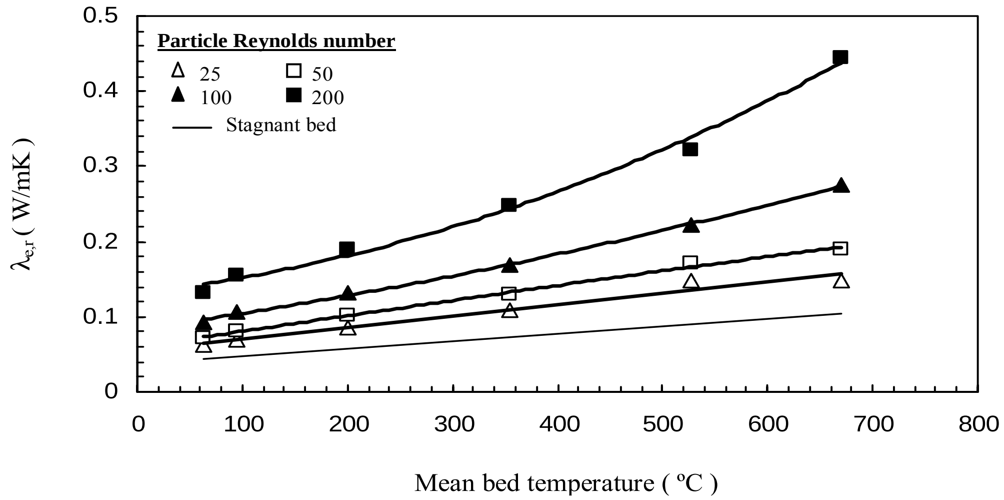


Fig. (9): Change of effective radial thermal conductivity for cylindrical pecked bed of alumina spheres with mean bed temperature at different particle Reynolds number.

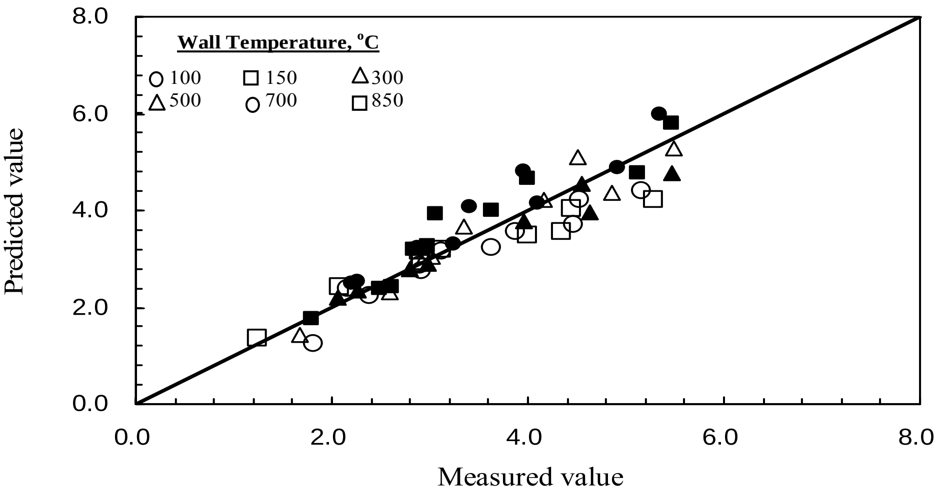


Fig. (10): Comparison between measured and predicted effective radial thermal conductivity for packed bed of alumina spheres.

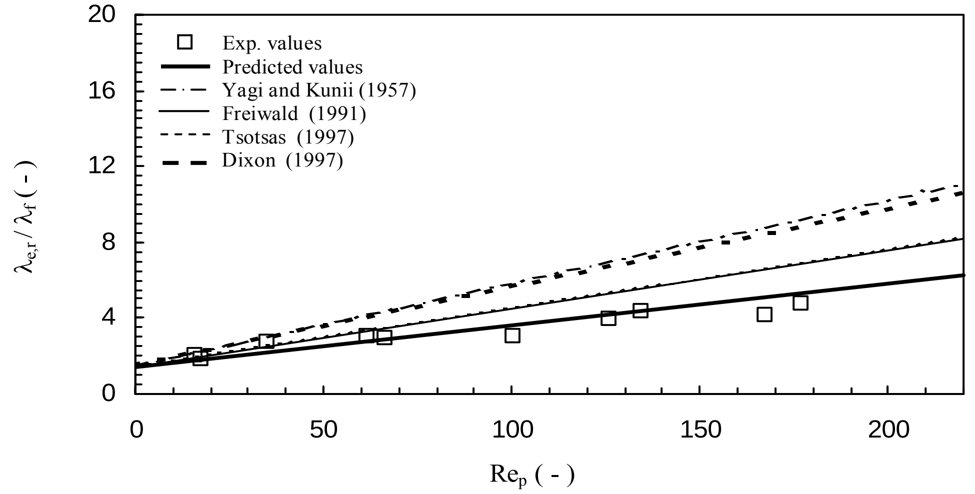
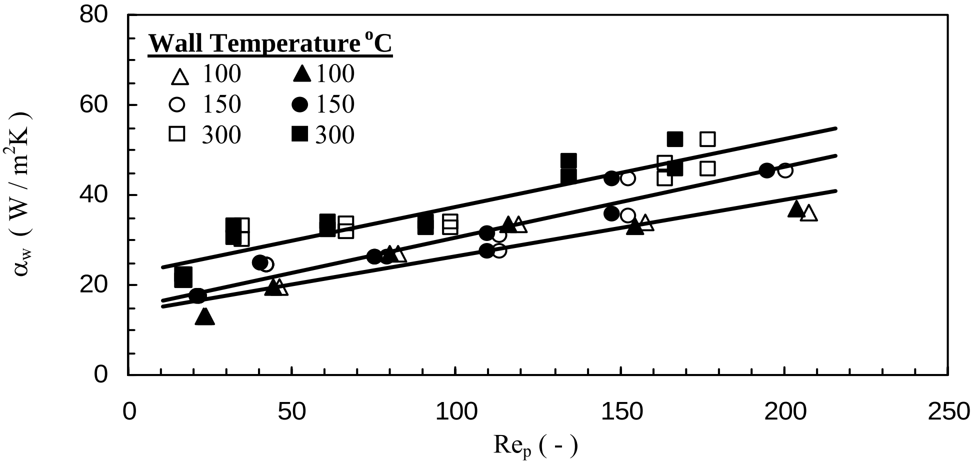
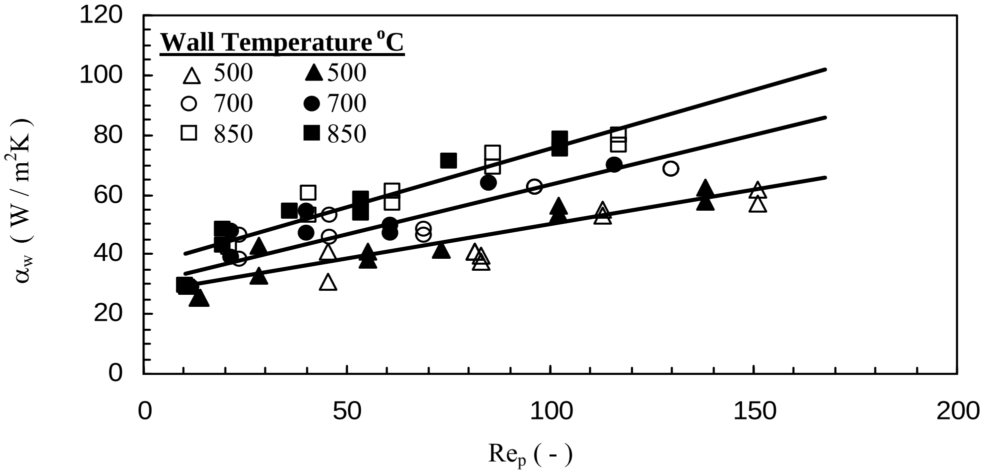


Fig. (11): Comparison of predicted effective radial thermal conductivity with its values in literatures as a function of particle Reynolds number for packed bed of alumina spheres, $T_w = 300\ ^oC$.



Open sign is level 2 , Closed sign is level 3

Fig. (12): Wall heat transfer coefficient as a function of particle Reynolds number for packed bed of alumina spheres, effect parameters are wall temperature and bed height.



Open sign is level 2 , Closed sign is level 3

Fig. (13): Wall heat transfer coefficient as a function of particle Reynolds number for packed bed of alumina spheres, effect parameters are wall temperature and bed height.

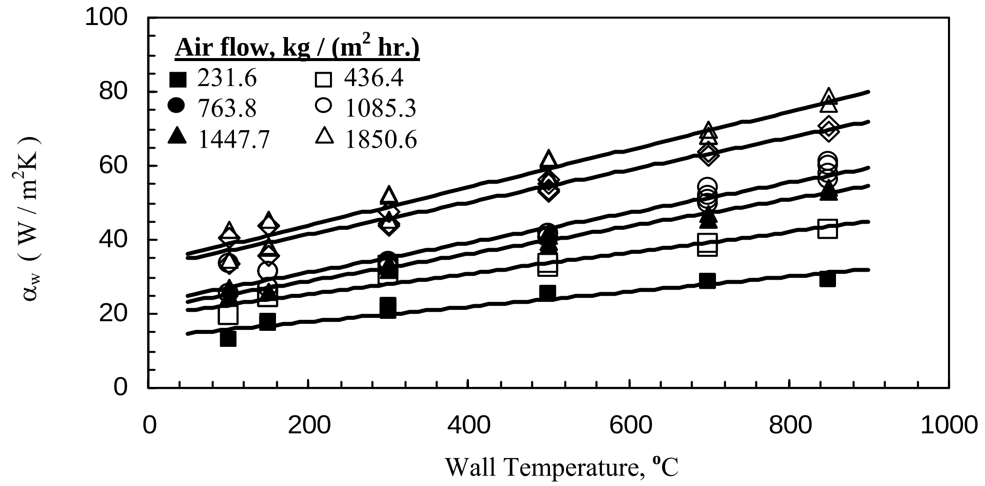


Fig. (14): Change of wall heat transfer coefficient with bed temperature for packed bed of alumina spheres.