International Journal for Research in Engineering Application & Management (IJREAM)
ISSN : 2454-9150 Vol-06, Issue-03, June 2020

Experimental Heat Transfer and Pressure Drop Studies in Packed Bed Columns with Nanofluids

G. Srinivasa Rao

Department of Mechanical Engineering, Kakatiya Institute of Technology and Science, Warangal-506015, India . *Corresponding author e-mail: gsrkits@gmail.com

Abstract - Various manufacturing and process industries use packed bed columns to transfer heat. The heat transfer mainly depends on bed void fraction, bed material and the properties of the fluid. Conventional liquids such as water have higher heat transfer coefficients compared to gases such as air. Nanofluid is a liquid dispersed with metal and metal oxide particles of nanometer size in a base liquid such as water. The nanofluids show a significant increase in the values thermal conductivity which increases with the concentration and temperature. At low values of concentration and operating temperature of about 35°C, experiments with nanofluids indicate higher heat transfer rates when compared to water. Equations are available for the estimation of Nusselt number and pressure drop for different conditions of flow of conventional fluids in tubes and conduits. Equations developed can be used for the estimation of heat transfer of nanofluids through packed bed columns. The salient outcomes of the state of art of research in packed beds listed.

Keywords: packed bed, nanofluid, heat transfer, pressure drop ,friction factor

INTRODUCTION

The heat transfer in a packed bed takes place between the liquid and packed material. The heat transfer through packed beds has wide applications in chemical and process industries. The analysis of experimental heat transfer coefficients and pressure drop is for flow of nanofluid through a packed bed column. However, such experiments with nanofluids have not been reported till now. The present work outlines the key characteristic of heat transfer and pressure drop undertaken with conventional fluids such as air and water. The determination of heat transfer coefficient and pressure drop is for flow of nanofluids in packed bed columns.

2.0 Determination of Pressure Drop And Heat Transfer

The friction factor for flow of fluid in a packed bed column is determined from the relation

$$\mathrm{f} = \frac{\Delta \mathrm{P}}{\mathrm{L_b}} \frac{D_P}{\rho V_S^2} \left(\frac{\varepsilon^3}{1-\varepsilon} \right) \qquad (1)$$

The equation of Ergun [7] is used for the estimation of pressure drop given by

$$\Delta \mathrm{P} = \frac{150 \mu \mathrm{V_s L_b}}{\mathrm{D_p^2}} \frac{(1-\varepsilon)^2}{\varepsilon^3} + \frac{1.75 \rho \mathrm{V_s^2 L_b}}{\mathrm{D_p}} \frac{(1-\varepsilon)}{\varepsilon^3} \qquad (2)$$

where ε is the bed void fraction and can be determined from the relation $\varepsilon = 1 - V_p / V_b$, in which V_p and V_b are volume of particles and volume of bed respectively. V_s is superficial velocity D_p is particle equivalent diameter given in the form $D_p = 6 V_p / S_p$ and S_p is surface area of the particle. The experimental pressure drop is calculated with the equation given by

$$\Delta P_{exp} = R_m (\rho_A - \rho_{bf}) g / g_c \qquad (3)$$

The pressure drop estimated with Eq.(1) for different flow rates are compared with the experimental values and presented in the form of graphs. Theoretical and experimental friction factors are calculated by using the Ergun[7].The early works on packed bed heat transfer are due to Anzelius [1], although Schumann [21], is usually cited in most studies. Both the authors assumed the fluid to be incompressible, and obtained expression for the evaluation of heat transfer coefficient. They assumed the fluid to flow uniformly through a bed of solid particles with perfect conductivity between the particles. The derived heat transfer equation is given by

$$T_s = (T_{fi} - T_{si}) \int_0^\infty I_0 \left(2\sqrt{YZ} \right) e^{-Y} e^{-Z} dZ + T_{si} \qquad (4)$$

Equation (1) can be modified and written as

$$T_f - T_s = (T_{fi} - T_{si}) I_0 \left(2\sqrt{YZ} \right) e^{-Y} e^{-Z} \qquad (5)$$

$$\frac{T_f - T_s}{T_{fi} - T_{si}} = I_0 \left(2\sqrt{YZ} \right) e^{-Y} e^{-Z} \qquad (6)$$

DOI : 10.35291/2454-9150.2020.0489

Where $Y = \frac{h_f a z}{\rho_f C p_f V_f}$ and $Z = \frac{h_f a\theta}{\rho_f C p_f (1-\varepsilon)}$ (7)

The solutions of these equations presented in graphical from are called Schumann curves. Furnas [8] extended the Schumann curves to a wide range of temperatures. An empirical relation for the evaluation of the heat transfer coefficient developed is given by

$$h_V = \frac{AG^{0.7}T^{0.3}10^{\left(0.68\varepsilon - 3.56\varepsilon^2\right)}}{D_p^{0.9}} \qquad (8)$$

Saunders and Ford [22] used dimensional analysis to obtain an equation for the estimation of heat transfer coefficients. The research was however limited to spheres and cannot be applied to other geometries of solid particles. Kays and London [10] presented a correlation for the evaluation of heat transfer coefficients between a gas and randomly packed solid spheres with the Colburn j- factor. The correlation equation given is

$$j_H = 0.23/\mathrm{Re}_p^{0.3} \; j_H = \mathrm{St}\,\mathrm{Pr}^{0.66} \quad \text{for} \qquad (9)$$

$(200<\mathrm{Re}_P<50{,}000 \text{and} 0.37<\varepsilon<0.39)$

Lof and Hawley [14] investigated the heat transfer between air and packed bed of granite gravel. The unsteady state heat transfer was correlated with air mass velocity and particle diameter valid in the range of $8 < D_p < 33\,\mathrm{mm}$ $0 < \mathrm{Re}_p < 500$ and $311 < T_b < 394\mathrm{K}$. The equation obtained is given by

$$h_V = 0.652\left(\frac{G}{D_P}\right)^{0.7} \qquad (10)$$

Leva [13 -15] determined the heat transfer coefficient between smooth spheres of low thermal conductivities of size 6.8 mm and fluids (air and carbon dioxide) in packed beds and tubes (column) diameters of 50.8mm. The ratio of particles to tube diameters D_P/D_t was varied from 0.008 - 0.27. Fluid flow rate was of Reynolds number range 250 – 3000. Correlation of film coefficient was found to be

$$h = 3.50\left(k/D_t\right) \mathrm{Exp}\left[-4.6\left(D_P/D_t\right)\left(D_P G/\mu\right)^{0.7}\right] \qquad (11)$$

And a modified form is given as

$$h = 0.40\frac{k}{D_t}\left(\frac{D_P G}{\mu}\right)^{0.7} \qquad (12)$$

Ball [2], Norton [17], Meek [15], Bradshaw et al. [4] has worked on various packed beds using air and other gases as fluids and developed correlations for heat transfer coefficient. Barker [3] has given extensive reviews on these works and compared the results obtained by these authors. Baldwin [5] has developed correlations for the estimation of heat transfer of water flowing through bed of spheres in the range 3000<Re<70,000 for regular cubic arrangement having a void fraction of $\varepsilon = 0.47$

$$j_H = 0.992/\mathrm{Re}^{0.33} \qquad (13)$$

for dense cubic arrangement having ε = 0.261 as

$$0.940\mathrm{Re}^{0.30} \qquad (14)$$

Shen *et al.* [23] performed experiments at low values of Reynolds number in the range of 5 to 229 with 1.3 and 2.7mm glass beads packed inside a 63 mm diameter polystyrene cylinder. Based on their experimental observations, they observed that the correlation developed by Gunn [9] could predict their data for a wide range of porosities between 0.35 and 1.0 and Reynolds numbers up to 10^5

$$\mathrm{Nu} = \frac{hD_P}{k_f} = 7 \quad 10\varepsilon + 5\varepsilon^2 \quad 1 + 0.7\mathrm{Re}_P^{0.2}\mathrm{Pr}^{1/3} \; + \; 2.4\varepsilon + 1.2\varepsilon^2 \quad \mathrm{Re}_P^{0.7}\mathrm{Pr}^{1/3} \qquad (15)$$

Wakao *et al.* [25] have presented a correlation that is corrected for axial fluid thermal dispersion

$$\mathrm{Nu} = \frac{hD_P}{k_f} = 2 = 1.1\mathrm{Re}_P^{0.6}\mathrm{Pr}^{0.33}$$

for $15 < \mathrm{Re}_p < 8500$ (16)

Nsofor and Adebiyi [16], when referring to Wakao *et al.* [25] presented similar equation as

$$\mathrm{Nu} = \frac{hD_P}{k_f} = 2 + 1.1\left[6(1-\varepsilon)\right]^{0.6}\mathrm{Re}_P^{0.6}\mathrm{Pr}^{1/3} \qquad (17)$$

while Schroder *et al.*[20] used the structure of the equation given by Wakao *et al.*, Dixon and Cresswell [6] pursued a theoretical model for the prediction of heat transfer in radial fluid flow in packed beds. The correlation suggested by them is valid for Rep >100 and a bed to particle size ratio > 8.

$$\mathrm{Nu} = \frac{hD_P}{k_f} = \frac{0.255}{\varepsilon}\mathrm{Re}_P^{0.67}\mathrm{Pr}^{1/3} \qquad (18)$$

k_f is the fluid thermal conductivity. The experimental investigation undertaken by various authors is presented next..

III. The Physical Properties of Nano Fluids

The density and specific heat of nanofluid at different volume concentrations are estimated using the following relations valid for homogeneous mixture given by

$$\rho_{nf} = \phi\,\rho_p + (1-\phi)\,\rho_{bf} \qquad (20)$$

$$C_{p_{nf}} = \frac{(1-\phi)\left(\rho\,C_p\right)_{bf} + \phi\left(\rho C_p\right)_p}{(1-\phi)\rho_{bf} + \phi\rho_p} \qquad (21)$$

The experimental data of viscosity available in literature for Cu, CuO, Al_2O_3, TiO_2, SiO_2, ZrO_2, ZnO nanoparticles dispersed in water is subjected to regression by Sharma et al. [2012] for $0 \le \phi \le 3.7$, $20 \le T_b \le 70$, $20 \le d_p \le 170$. The equation is obtained with a deviation

DOI : 10.35291/2454-9150.2020.0489

of less than 10% where ϕ is in percent, T_b in ^{0}C and d_p in *nm* as

$$\frac{\mu_{nf}}{\mu_w} = C_1\left(1+\frac{\phi}{100}\right)^{11.3}\left(1+\frac{T_{nf}}{70}\right)^{-0.038}\left(1+\frac{d_p}{170}\right)^{-0.061} \qquad (22)$$

$C_1 = 1.4$ for SiC nanofluid and $C_1 = 1.0$ for other water based nanofluids.

Different models for the determination of effective thermal conductivity of two phase solid-liquid mixtures are developed from the classical Maxwell [29] equation given as

$$k_{eff} = k_{bf}\left[\frac{k_p + 2k_{bf} + 2\phi(k_p - k_{bf})}{k_p + 2k_{bf} - \phi(k_p - k_{bf})}\right] \qquad (11)$$

Vajjha and Das [28] proposed the following equation to estimate thermal conductivity of

$$k_{nf} = \frac{k_p + 2k_f + 2(k_p \quad k_f)\varphi}{k_p + 2k_f \quad (k_p \quad k_f)\varphi}k_f + 5\times10^{4}\beta\varphi\rho_f Cp_f\sqrt{\frac{k_b T}{\rho_p d_p}}f(T,\varphi) \qquad (23)$$

Sharma et al. [30] developed an equation for the determination of thermal conductivity of Cu, CuO, Al_2O_3, TiO_2, SiO_2, ZrO_2, ZnO nanoparticles dispersed in water valid in the range $0 \le \phi \le 3.7$, $20 \le T_b \le 70$, $20 \le d_p \le 170$. The equation is obtained as

$$\frac{k_{nf}}{k_w} = \left[0.8938\left(1+\frac{\phi}{100}\right)^{1.37}\left(1+\frac{T_{nf}}{70}\right)^{0.2777}\left(1+\frac{d_p}{150}\right)^{-0.0336}\left(\frac{\alpha_p}{\alpha_w}\right)^{0.01737}\right] \qquad (24)$$

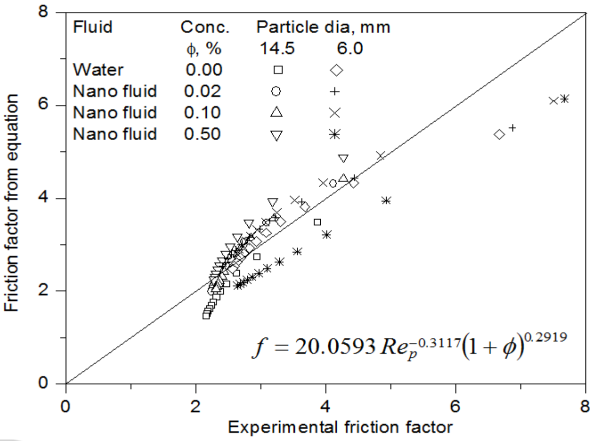

Fig. 1 Comparison of experimental and theoretical friction factor for water and nano fluids

3.0 Experimental Review on packed bed heat transfer

Author	System	Method of heating	Range of Reynolds number (Re_P) used	Correlation
Baumeister and Bennet (1958)	Air- Steel	Electrical induction (Steady state)	200 – 10400	$j_h = 1.09Re_P$
Bradshaw and Mayer (1963)	Air –celite cylinders, etc	water soaked packing's dried by air at room temperature	300 – 2500	$j_h = 2.52(Re_P)^{0.5}$
Bunnel et.al (1949)	Air –alumina	Heated airbed wall Maintained at boiling point of water	30 – 150	$K_{er}/K_{ef} = 5.0+0.061Re_P$
Coberly and Marshall (1951)	Air celite	Steam heated walls	70 - 300	Ke= 0.018+0.00098Rep
Colbum (1931)	Air pebbles, granules, pellets, Porcelain balls, etc	Steam-jacketed packed tube	G : 1 – 9	$h = 8aCpv^2G^{0.23}$ $a = f(D_P/D_t)$
Furmas (1930)	Air – iron spheres	Heated air	120 – 1200	$h = 6.91X10^{-3}X\ Gr^{0.75}t_fXG\text{-}1.75$
Gamson *et.al* (1943)	Air –celite spheres dried by air Cylinders	Water soaked packing	40 -4000	$J_h=1.064XRep^{0.41}$ $Re>35; J_h=1.81X\ Re_P^{-10}$; $Re_P<40$
Glasser and Thodos (1958)	Air – ceramic/ brass spheres	Transient heating by regenerating technique Steady –state heating	330 – 1500 300 – 4000	$Nu = 1.25Re_P^{0.56}$ $300<Re_P<4000$
Gupta and Thodos(1962a)	Existing data of single sphere	Electrical heating	33 – 6500 Re>20	$\varepsilon jh = 0.0108+ 0.929/Re_P^{0.58}$
Gupta and Thodos(1962b)	Air-celite spheres	Water –soaked particles dried by air	95 – 2500	$\varepsilon jh = 2.06/Re_P^{0.28}$
Houghen and Piret(1951)	Air – celite spheres bed	heated air entering the	193 – 2824	$K_e/C_P\mu = 3.7/\varepsilon\ x(Re_P)^{1/3}$

Leva (1947)	Air –smooth Spheres	Heated walls	500 – 3408	$h = 0.813\ k_f/Dt$ $e\text{-}^{0.6(Dp/Dt)}.Re_P^{0.9}$
Leva and Grummer (1948)	Air –smooth spheres	Heated walls	500 – 3408 .7	$h = 0.813k_f$
Leva *et.al* (1948)	Air smooth spheres	Heat air and Co_2 bed wall is cooled	250 – 3000	$h = 3.5k_f/Dt$ $D_{t.}e^{-6(DP/Dt)}Re_P^{0.7}$
Lindauter (1967)	Air –steel and tungsten	Electrical resistance heating to produce Sinusoidal gas Temperature	23 – 18200	------
Wakao and Kato (1969)	Air glass carboroundum	concentric electric Heater	-----	$K_e/K_f=(K_e/k_f)_{Nur}=$ $0+0.707$ $Nu_t^{0.96}(k_e/k_f)^{1.11}$
Yagi and $K_e/K_f=B+Re_PPr_P$, Kunii (1957)	Air- iron/ Porcelain cement clinker, fire brick and Raschig rings	coaxial electric heater at the center, outside wall is insulated with fire brick	----- ----- ------	

IV. HEAT TRANSFER WITH NANO FLUIDS

The nanofluids show a superior potential for increasing heat transfer rates in a variety of cases. Different theories have been proposed to explain heat transfer enhancement. Early experiments with nanofluid for the determination of heat transfer coefficients have been undertaken by Pak and Cho [18] and Xuan and Li [26-27] in the turbulent Reynolds number range. They developed empirical correlations for the estimation of Nusselt number using nanofluids dispersed in water with TiO2, Al2O3 and CuO nanoparticles. The results indicate a remarkable increase in heat transfer coefficients compared to base fluid at the same Reynolds number. The nanofluids have shown an increase in heat transfer coefficient over that of water in the low volume concentration less than 1.0% undertaken.

Wen and Ding [24] measured the local heat transfer coefficients along the tube length during laminar flow. They conducted experiments with γ- Al2O3 nanofluid dispersed in water for forced convection in a copper tube of inner diameter 4.5mm and 970mm long. The correlation of Shah [19] for thermal entry length under constant heat flux is given by

$$Nu = 4.364 + 0.0722\left(RePr\frac{D}{x}\right)$$

$$\text{for } \left(RePrD/x\right) < 33.3 \qquad (19)$$

$$Nu = 1.953\left(RePr\frac{D}{x}\right)^{1/3} \quad \text{for } \left(RePrD/x\right) \geq 33.3 \qquad (20)$$

Most of the research investigated in this review paper was for laminar forced convection in a tube, with or without the packing material because there is very little research on forced convection in packed beds with nano fluids with different concentration. All of the research studied in this review paper reported increases in heat transfer due to the addition of nanoparticles in the base fluid. From the Figure1.0 to Figure4.0 the following conclusions are noted. The friction factor increases with lowering particle diameters and increasing concentration of the nanofluid. A regression equation is obtained for the estimation of friction factor with an average deviation of ±0.08% and standard deviation of 1.68%

$$f = 20.0593Re_p^{-0.3117}(1+\varphi)^{0.2919} \qquad (21)$$

A regression equation is developed for the estimation of Nusselt number as a function of particle Reynolds number, Prandtl and volume concentration of nanofluid. It is obtained with a standard deviation of 1.56% and an average deviation of -3.92% given by

$$Nu = 0.188Re_p^{0.98}(1+\varphi)^{0.5310}Pr^{-0.4403} \qquad (22)$$

V. CONCLUSIONS

However, the following trends are in general agreement with all researchers

(i) There is an enhancement in the heat transfer coefficient with increasing Reynolds number in packed beds
(ii) The heat transfer coefficient increases with nanoparticle volume fraction.
(iii) The heat transfer coefficient increases with fluid temperature, though not significant.
(iv) The heat transfer coefficient increases with the diameter of the packing material.
(v) There is enhancement of heat transfer coefficient with decreasing in void fraction.

DOI : 10.35291/2454-9150.2020.0489

(vi) The heat transfer coefficient changes with packing material properties.

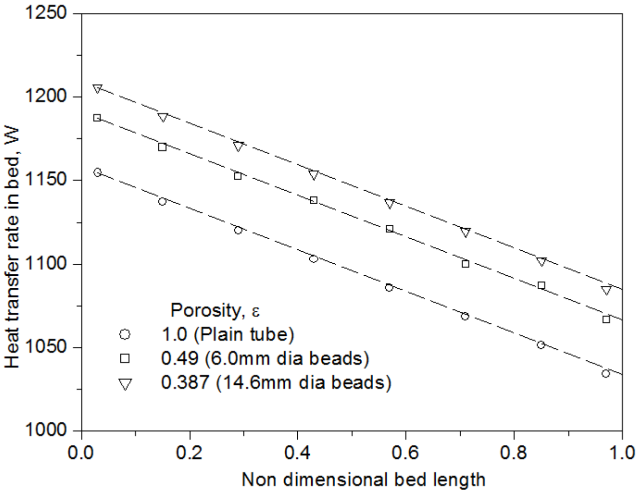

Fig. 2 Variation of heat transfer rate with non-dimensional bed length

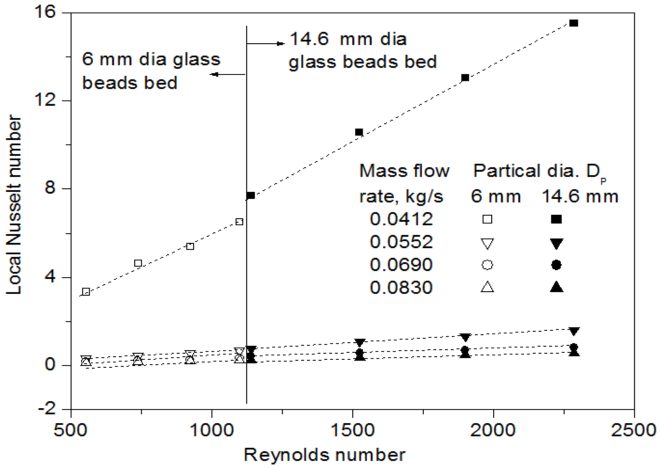

Fig. 3.Effect of Reynolds number on local Nusselt Numbers

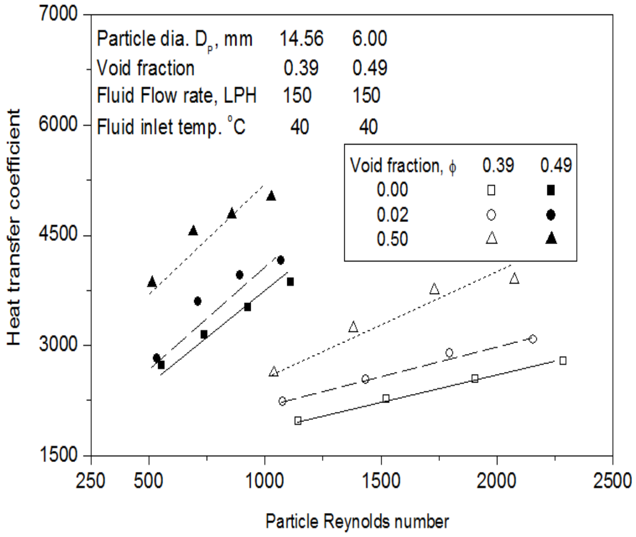

Fig.4 Variation of heat transfer coefficient with Particle Reynolds number

Nomenclature

A, C	*constants*	[-]
Cp	*specific heat*	[J/KgK]
$\bar{D}$	*hydraulic diameter*	[m]
D	*diameter*	[m]
f	*friction factor*	[-]
G	*mass flow rate*	[Kg/sec]
g	*acceleration due to gravity*	
g_c	*local acceleration due to gravity*	
h	*heat transfer coefficient*	[W/m^2]
h_v	*volumetric heat transfer coefficient*	*[W/m^3]*
I_0	*Bessel's function of first kind*	[ ]
j	*colburn factor*	[J]
k	*thermal conductivity*	[W/mK]
L	*length*	*[m]*
m, n	*constant*	*[-]*
Nu	*Nusselt Number*	*[-]*
Pr	*Prandtl Number*	*[-]*
Pe	*Peclet Number*	*[-]*
T	*temperature*	*[K]*
ΔP	*pressure drop*	*[Pascal]*
Re	*Reynolds number*	*[-]*
V	*velocity*	*[m/sec]*
x	*axial distance*	*[m]*
St	*Stanton number*	*[-]*
xf	*total frictional faction*	*[Pascal]*
Δx	*displacement in axial distance of total pressure drop*	*[m]*
Y	*constant*	*[-]*
Z	*constant*	*[-]*

Subscripts

s	*superficial*
D	*diameter*
f	*fluid*
W	*wall*
fi	*fluid inlet*
s_i	*solid inlet*
P	*particle*
er	*effective radial*
ef	*effective*

Greek symbols

θ	non dimensional temperature	[-]
ρ	density	[kg/m^3]
ε	void fraction	
µ	viscosity	[N-sec/m]
ϕ	nano particle volume concentration	[%]

REFERENCES

[1] Anzelius A.1926 *J. Mechanical* **6** 291 -296.

[2] Ball W.E 1958 *Determination by a frequency resonance Technique Abstract* **19** 494.

DOI : 10.35291/2454-9150.2020.0489

[3] Barker J.J 1965 *J. Indus. Eng. Chem. Process Design Develop* **57(4)** 43-51

[4] Bradshaw R.C and J.E Myers 1963 *J. Porous media* **4** 23-28

[5] Baldwin D.E 1961 *Industrial and Engineering chemistry process Design and Development* ACS Publication **5(3)** 281-284

[6] Dixon A.G and Cresswell D.L 1979. *American Institute of Chemical Engineers (AIChE) Journal*, **25.4** 663-676

[7] Ergun and Sadri 1952 *J. Chemical Engineering Progress* **Vol.4** 289-294

[8] Furmas C.C.1930. *J.Chem Eng* **22: 26** and 721.

[9] Gunn D.J.1978. *Int. Journal of Heat and Mass Transfer* **21.4** 467-476

[10] Kays W.M and A.C London 1964 *Compact Heat Exchangers* **McGraw-Hill** .New York

[11] Leva M., 1947 *Ind .Chem .Eng Fudamn*, **39:** 857 – 859

[12] Leva and Grummer 1948. *Ind. Chem. Eng. Fundmn***40** 747-753.

[13] [13] Leva M.M., Weintraub M., Grummer and E.L. Clark 1948.*J.Ind. Eng***40** 747-752Loaf G.O.G and [14] R.W Hawley 1948. *J. Ind. Eng.*, **40(6)** 1061 – 1070.

[14] Meek, R.M.G.1961. *International Heat Transfer Development"* . **ASME New York.**

[15] Nsofor E.C and Adebiyi G.A. 2001. "*Experimental Thermal and Fluid Science*, **24**: 1-9

[16] Norton C.L. 1946 J. *Am. Ceramic Soc.*, **29:187**-193.

[17] Pak B.C. and Cho, Y.I. 1998 Exp. *Heat Transfer* **11 (2)** 151-170.

[18] Shah R. K.1975 *Paper HMT -11 -75. Proc. 3rd National Heat Mass Transfer Conference Indian Institute of Technology*, ***Bombay India*** **Vol. 1**

[19] Schroder E. Class, A. Krebs L. 2006. *Experimental Thermal and Fluid Science*, **30.6** 545 – 558

[20] Schumann, T.E.W, 1929. *J. Heat Transfer* 208 - 212.

[21] Saunders O.A. and Ford 1940 *J Iron and Steel* **141** 291- 296.

[22] ShenJ.,Kaguei S, andWakao, N.1981.J.Chemical *Engineering Science* **36** 1283 - 1286

[23] Wen, D., and Y. Ding 2004. *Int. J. Heat Mass Transfer* **47** 5181–5188

[24] Wakao N. Kaguei S and Funazkri, T.1979 *J. Chemical Engineering Science*, **34** 325- 336

[25] Xuan Y and Q. Li 2000 *Int. J. Heat and Fluid Flow* **21** 58–64.

[26] Xuan, Y., and Q. Li (2003). *J. Heat Transfer* **125(1)** 151-155

[27] Vajjha, R. S. and Das, Debendra K., Experimental determination of thermal conductivity of three nanofluids and development of new correlations, International Journal of Heat and Mass Transfer 52 (2009) 4675-4682

[28] J.C.Maxwell, 1881 "A Treastise on Electrical and Magnetism," Oxford University Press, Cambridge, UK, 2nd edition,.

[29] Sharma, K.V. Sarma, P.K., Azmi W.H., Rizalman Mamat., Noor .M, Kadirgama K.," 2012 Estimation of turbulent forced convection heat transfer coefficients of water based nanofluids", ICMER-1 Vol.1, pp.1-31.

DOI : 10.35291/2454-9150.2020.0489