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Natural Convection Heat Transfer from Inclined Cylinders: A Unified Correlation

Neetu Rani, Hema Setia, Marut Dutt. R.K. Wanchoo

Abstract**—**An empirical correlation for predicting the heat transfer coefficient for a cylinder under free convection, inclined at any arbitrary angle with the horizontal has been developed in terms of Nusselt number, Prandtl number and Grashof number. Available experimental data was used to determine the parameters for the proposed correlation. The proposed correlation predicts the available data well within ±10%, for Prandtl number in the range 0.68-0.72 and Grashof number in the range 1.4×10^4–1.2×10^{10}.

Keywords**—**Heat transfer, inclined cylinders, natural convection, Nusselt number, Prandtl number, Grashof number.

I. Introduction

NATURAL convective heat transfer in cylindrical geometry has been widely studied for its applications in heat loss from piping, heat exchangers, HVAC systems etc. Natural convection heat transfer phenomena are two dimensional on vertical and horizontal cylinders but are three dimensional on inclined cylinders due to the circumferential and axial developments of the boundary layers making the flow as well as heat transfer behavior complex [1]. A number of correlations are available in literature for the estimation of natural convection heat transfer from vertical as well as horizontal cylinders, but little work has been reported on the effect of cylinder inclination on the mean heat transfer coefficient. An extensive review on the free convection heat transfer from vertical cylinders has been presented by Popiel [2]. Sparrow and Gregg [3] provided the first approximate solution for laminar free convection flow of air over a vertical cylinder with uniform surface temperature by applying the similarity method. Churchill and Chu [4] have developed empirical correlations for estimating the mean value of Nusselt number applicable for uniform heating as well as for uniform wall temperature, for mass transfer and for simultaneous heat and mass transfer. Cebeci [5] numerically studied free convection heat transfer from slender cylinders with a uniform surface heat flux for different Prandlt numbers using a finite difference technique. Experimental and analytical free convection heat transfer from vertical cylinders has also been studied by Nagendra et al. [6], Arshad et al. [7], Morgan [8], Oosthuizen [9], and Kimura [10].

Sugiyama et al. [11] have studied the heat transfer characteristics of natural convection around a horizontal cylinder immersed in liquid metal. Leonenko and Antipin [12] also worked on horizontal cylinders and suggested that there exists a diffusive boundary layer apart from the dynamic and thermal layer at near critical state when the coefficient of diffusion is less than the thermal diffusivity of the system which is influential in heat transfer. Several other researchers like Reymond et al. [13], Clemes et al. [14], Fand and Morris [15] have also worked on developing correlations for predicting the heat transfer in horizontal cylinders.

Some studies of natural convection heat transfer from inclined cylinders have also been undertaken. Koch [16] used the equation for horizontal cylinders with the diameter as the characteristic length to the case of inclined cylinders. The effect of cylinder inclination on natural convective heat transfer coefficient has been studied by Muhaddin [17]. All experiments were conducted in air at atmospheric pressure. Grashof number ranged between 1.4×10^4 and 5.5×10^5. Oosthuizen [18] carried out experiments to determine the mean heat transfer rates for free convection from cylinders inclined at an angle θ to the horizontal. Al-Arabi and Salman [19] and Al Arabi and Khamis [20] experimentally studied natural convective heat transfer from inclined cylinders with uniform surface temperature in air. They used cylinders with different aspect ratio and found that the heat transfer rate is a function of both the diameter and the angle of inclination. Correlations were developed to evaluate the local and average Nusselt number for inclined cylinders. A unified approach for horizontal and inclined cylinders for natural convection heat transfer with different angles of inclination has been investigated by Chand and Vir [21]. Gupta [22] extended the work of Bansal [23] and reported his work on natural convection heat transfer from horizontal cylinders in the Grashof number range of 1.04×10^6 to 2.86×10^6 and on inclined cylinders in the Grashof number range of 9.44×10^5 to 2.39×10^7. Heo and Chung [24] also investigated natural convective heat transfer on the outer surface of inclined cylinders.

Although natural convection heat transfer from a single vertical and a horizontal cylinder has been investigated extensively, limited information is available on the effect of inclination angle on natural convective heat transfer inside cylindrical enclosures. Correlations available in the literature are data specific and thus fail to predict the whole range of data. Hence, there is a need to develop a unified correlation. In the present study, based on experimental data of Bansal [23] a

Neetu Rani was a post graduate student at University Institute of Chemical Engineering and Technology, Panjab University, Chandigarh, India.
Hema Setia is assistant professor at University Institute of Engineering and Technology, Panjab University, Chandigarh.
Marut Dutt was an undergraduate student at University Institute of Chemical Engineering and Technology, Panjab University, Chandigarh, India.
R. K. Wanchoo is professor at University Institute of Chemical Engineering and Technology, Panjab University, Chandigarh, India (e-mail: wanchoo@pu.ac.in).

unified correlation has been proposed for predicting the heat transfer coefficient from horizontal, vertical and inclined cylinders in terms of Nusselt number (Nu), Prandtl number (Pr) and Grashof number (Gr). The angle of inclination (θ) varies from 0° to 90°. The experimental range of the Prandtl number ranges from 0.68-0.72 and Grashof number varies from 1.4×10^4–1.2×10^{10}. The proposed correlation was tested with the data available in literature on the subject and is found to predict the data well within ±10%.

II. Mathematical Formulation of the Problem

The conservation equations for mass, momentum, and energy for laminar free convection in a boundary layer on a vertical cylinder (see Fig. 1) can be expressed as:

$$\frac{\partial(ru)}{\partial x}+\frac{\partial(rv)}{\partial r}=0 \tag{1}$$

$$\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial r}=g\beta(T-T_\infty)+\frac{\nu}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u}{\partial r}\right) \tag{2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial r}=\frac{\alpha}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) \tag{3}$$

To determine the dimensionless groups for heat transfer in free convection, (1) to (3) can be transformed in dimensionless form using the following dimensionless parameters:

$$R=\frac{r}{L_c}\ ;\quad X=\frac{x}{L_c}\ ;\quad U=\frac{u}{U_0}\ ;\quad V=\frac{v}{U_0}\ ;\quad \theta=\frac{T-T_\infty}{T_w-T_\infty}$$

where L_c is a characteristic length, U_0 is a reference velocity, T_w is the wall surface temperature, and T_∞ is the fluid temperature at distances away from the hot cylinder. The resulting non-dimensional equations are:

$$\frac{\partial(U)}{\partial X}+\frac{\partial(V)}{\partial R}=0 \tag{4}$$

$$U\frac{\partial U}{\partial X}+V\frac{\partial V}{\partial R}=\frac{g\beta(T_w-T_\infty)L_c}{{U_0}^2}\theta+\frac{\nu}{U_0L_c}\left[\frac{1}{R}\frac{\partial}{\partial R}\left(R\frac{\partial U}{\partial R}\right)\right] \tag{5}$$

$$U\frac{\partial\theta}{\partial X}+V\frac{\partial\theta}{\partial R}=\frac{\alpha}{U_0L_c}\left[\frac{1}{R}\frac{\partial}{\partial R}\left(R\frac{\partial\theta}{\partial R}\right)\right] \tag{6}$$

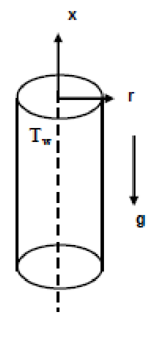

Fig. 1 Vertical cylinder

TABLE I
VALUE OF REGRESSION COEFFICIENTS

Correlation	a	b	R^2
(16)	0.216±0.008	0.307±0.001	0.995
(17)	0.742±0.005	-	0.995
(18)	0.1237±0.0005	-	0.981
(19)	0.390±0.008	0.1685±0.0006	0.996

The dimensionless group in the momentum equation can be rearranged as

$$\frac{g\beta(T_w-T_\infty)L_c}{U_0^2}=\frac{g\beta L_c^3(T_w-T_\infty)/\nu^2}{(L_cU_0/\nu)^2}\equiv\frac{Gr}{Re^2} \tag{7}$$

Grashof number, Gr is defined as

$$\frac{g\beta L^3(T_w-T_\infty)}{\nu^2} \tag{8}$$

Defining Reynolds number and Prandtl number as

$$Re=\frac{U_0L_c}{\nu}\qquad Pr=\frac{\nu}{\alpha} \tag{9}$$

Equations (4)-(6) can be written as

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial R}=0 \tag{10}$$

$$U\frac{\partial U}{\partial X}+V\frac{\partial V}{\partial R}=\frac{Gr}{Re^2}\theta+\frac{1}{Re}\left[\frac{1}{R}\frac{\partial}{\partial R}\left(R\frac{\partial U}{\partial R}\right)\right] \tag{11}$$

$$U\frac{\partial\theta}{\partial X}+V\frac{\partial\theta}{\partial R}=\frac{1}{Pr\,Re}\left[\frac{1}{R}\frac{\partial}{\partial R}\left(R\frac{\partial\theta}{\partial R}\right)\right] \tag{12}$$

As is apparent from (7), the dimensionless group $g\beta(T_w-T_\infty)L_c/U_0^2$ is a ratio of the buoyancy force to inertial force. In free convection, the buoyant forces are the only driving forces that generate the flow field because there is no external flow field. For such a case the Reynolds number appearing in the above equations cannot be an independent parameter because no external flow velocity exists. Then the Nusselt number characterizing the heat transfer coefficient for free convection from the surface is a function of the Prandtl and Grashof numbers and can be correlated by an equation of the form:

$$Nu=f(Gr\,Pr) \tag{13}$$

Similar approach can be used for horizontal and inclined cylinders to get the same relationship between Nu, Pr and Gr.

III. Characteristic Length

Functional form of (13) can in particular, be written as

$$Nu=a(Gr^bPr^c) \tag{14}$$

where Nu number and Gr number are based on a characteristic length L_c. Defining this characteristic length (L_c) as

$$L_c = \left[\frac{Ld}{(L/d)Cos\theta + (d/L)Sin\theta}\right]^{1/2} \quad (15)$$

As shown in Fig. 2, dSinθ is the longitudinal projection of cylinder diameter on horizontal axis and LCosθ is the longitudinal projection of cylinder length on horizontal axis.

From the definition of L_c, it is clear that when θ approaches 0° i.e. for horizontal cylinder L_c equals d, the cylinder diameter. For θ approaching 90° (vertical cylinder), L_c equals L, the cylinder length.

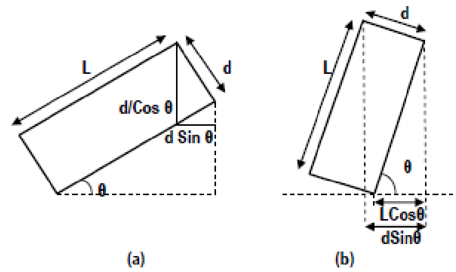

Fig. 2 Inclination with the horizontal (a) Small (b) Large

IV. Physical Interpretation of L_C

For horizontal cylinders, gravity force acts in the radial direction. So, the dimension characterizing the heat transfer is diameter of the cylinder. For vertical cylinders, gravity force acts in the vertical direction, therefore the characteristic dimension being length of the cylinder. But for the case of inclined cylinders, buoyancy force (gravity force) has a component normal, as well as parallel, to the surface. Hence, both, length and diameter contribute to free convection. So (15) could be taken as the representation of the length that characterizes an inclined cylinder.

V. Determination of Correlation Parameters

Four types of empirical correlations are tested in the present study:

$$Nu = a(Gr\ Pr)^b \quad (16)$$

$$Nu = a(Gr\ Pr)^{0.25} \quad (17)$$

$$Nu = a(Gr\ Pr)^{1/3} \quad (18)$$

$$Nu^{1/2} = 0.54 + a\left[\frac{PrGr}{\left\{1+\left(0.559/_{Pr}\right)^{9/16}\right\}^{16/9}}\right]^b \quad (19)$$

where Nu and Gr are based on the characteristic length defined by (15).

Equation (19) is of the form proposed by Churchill and Chu [4]. The parameters of (16)-(19) were calculated using the experimental data of Bansal [23]. The data were fitted to these equations and parameters a and b were calculated by minimizing the sum of square of errors using non linear regression techniques. The coefficients a and b are given in Table I. The available data covered the range of Prandlt and Grashof number of 0.68-0.72 and 1.4×10^4- 1.2×10^{10} respectively.

VI. Validity of the Correlations

To validate these correlations, available experimental data of researchers [14], [16], [18], [20], [22], [23], [25]-[27] on natural convection heat transfer from vertical, horizontal and inclined cylinders were used in (16)-(19) to predict the Nusselt number ($Nu_{calculated}$). The integrity of the proposed correlation was established using the minimum values of MRQE obtained for each correlation using the available data [3], [6], [16]-[18], [20], [23], [25], [27] MRQE (Mean relative quadratic error) was calculated as

$$MRQE = \sqrt{\frac{\Sigma\left(\frac{Nu_{experimental} - Nu_{calculated}}{Nu_{experimental}}\right)^2}{N-1}} \quad (20)$$

here N is the number of data points.

The calculated values of MRQE for the case of horizontal cylinder using the available correlations in comparison to the available experimental data are given in Table II. The MRQE values suggest that (19) predicts the data of Bansal [23], Koch [16] and Oosthuizen [18] with minimum error. In fact the error calculated with (19) is lower than that predicted by their own correlations. It is observed that all the correlations for horizontal cylinders fail to predict the data of Al Arabi and Khamis [20]. It is apparent from Fig. 3 that (19) predicts the data for all authors reasonably well within ±10% except for Al-Arabi and Khamis [20], Rice [27] and Clemes et al. [14] data.

In case of cylinders inclined at θ = 15°, 30° the MRQE calculated in comparison to correlation available in literature and (16)-(19) is given in Table III. The error was found to be minimum with (19) for Bansal [23] data. For cylinders inclined at θ = 45°, 60° the MRQE calculated in comparison to correlation available in literature and (16)-(19) is given in Table IV. The error was found to be minimum with (19) for Oosthuizen [18] data. Table V gives the MRQE calculated for cylinders inclined at θ =75°. Bansal [23] correlation showed the minimum error with his own data and the data of Muhhadin [17]. The error with (19) was higher for the data of Gupta [22] at θ =30° 45° and 65° and Al-Arabi and Khamis [20] for all cylinder inclinations, in comparison to their own correlations. However, (19) could predict all the available experimental data except for Al-Arabi and Khamis [20] well within ±10% as is evident from Fig. 4.

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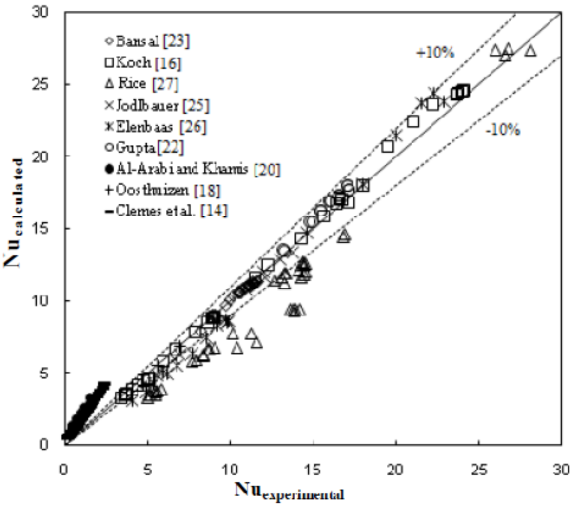

Fig. 3 Comparison of (19) with experimental data for free convective heat transfer from horizontal cylinder (θ = 0°)

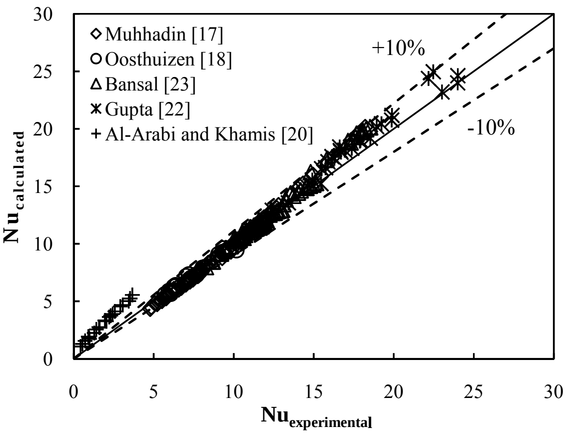

Fig. 4 Comparison of (19) with experimental data for heat transfer from cylinders inclined at θ=15°,30°,45°, 60° and 75°

TABLE II
MEAN RELATIVE QUADRATIC ERROR FOR ANGLE OF INCLINATION θ = 0°

Experimental Data→ Correlations ↓	Bansal [23]	Rice [27]	Koch [16]	Jodlbauer [25]	Elenbass [26]	Oosthuizen [18]	Gupta [22]	Clemes et al. [14]	Al-Arabi and Khamis [20]
Bansal [23]	0.0030	0.0355	0.0078	0.0172	0.0268	0.0232	0.0050	0.1820	0.3210
Muhaddin [17]	0.0310	0.0185	0.0288	0.0576	0.0213	0.1339	0.0447	0.0246	0.4128
Oosthuizen [9]	0.0051	0.0326	0.0075	0.0082	0.0220	0.0338	0.0041	0.1880	0.3299
Rice [27]	0.0109	0.0289	0.0108	0.0118	0.0173	0.0646	0.0133	0.2060	0.3554
Koch [16]	0.0086	0.0303	0.0092	0.0078	0.0200	0.0554	0.0097	0.2008	0.3478
Jodlbauer [25]	0.0050	0.0328	0.0075	0.0086	0.0230	0.0401	0.0041	0.1920	0.3350
Al-Arabi and Khamis [20]	0.0523	-	-	-	-	0.2557	0.0576	0.0508	0.0305
Present correlation (16)	0.0033	0.0444	0.0207	0.0360	0.0509	0.0659	0.0189	0.0310	0.1867
Present correlation (17)	0.1184	0.0506	0.1128	0.2617	0.1214	0.4732	0.1811	0.4430	0.6937
Present correlation (18)	0.0387	0.0668	0.0489	0.1140	0.0865	0.2129	0.0338	0.0390	0.0598
Present correlation (19)	0.0023	0.0371	0.0066	0.0206	0.0339	0.0071	0.0129	0.1850	0.2970

TABLE III
MEAN RELATIVE QUADRATIC ERROR FOR ANGLE OF INCLINATION θ = 15° AND 30°

Experimental Data→ Correlations ↓	Bansal [23]	Muhaddin [17]	Oosthuizen [18]	Gupta [22]	Bansal [23]	Muhaddin [17]	Oosthuizen [18]	Gupta [22]	Al-Arabi and Khamis [20]
θ→	15°	15°	15°	15°	30°	30°	30°	30°	30°
Bansal [23]	0.0035	0.0095	0.0147	0.0087	0.0044	0.0058	0.0136	0.0122	0.3660
Muhaddin [17]	0.0052	0.0277	0.1086	0.0729	0.0357	0.0280	0.0978	0.0840	0.4820
Oosthuizen [18]	0.0405	0.0069	0.0179	0.0118	0.0049	0.0069	0.0128	0.0210	0.3620
Gupta [22]	0.0030	0.0105	0.0138	0.0102	0.0039	0.0154	0.0306	0.0082	0.2790
Al-Arabi and Khamis [20]	0.0654	0.0885	0.2427	0.0727	0.0523	0.0695	0.6632	0.0763	0.0138
Present correlation (16)	0.0038	0.0340	0.0813	0.0366	0.0054	0.0285	0.0748	0.0340	0.1580
Present correlation (17)	0.1605	0.1472	0.4413	0.2870	0.1478	0.1529	0.4420	0.3040	0.9160
Present correlation (18)	0.0520	0.0814	0.2240	0.0479	0.0445	0.0769	0.2176	0.0561	0.0327
Present correlation (19)	0.0022	0.0160	0.0270	0.0270	0.0041	0.0120	0.0240	0.0230	0.3470

TABLE IV
MEAN RELATIVE QUADRATIC ERROR FOR ANGLE OF INCLINATION θ = 45° AND 60°

Experimental Data→ Correlations ↓	Bansal [23]	Muhaddin [17]	Oosthuizen [18]	Gupta [22]	Al-Arabi and Khamis [20]	Bansal [23]	Muhaddin [17]	Oosthuizen [18]	Gupta [22]	Al-Arabi and Khamis [20]
θ→	45°	45°	45°	45°	45°	60°	60°	60°	60°	60°
Bansal [23]	0.0064	0.0043	0.0229	0.0136	0.3193	0.0058	0.0016	0.0235	0.0096	0.3350
Muhaddin [17]	0.0350	0.0275	0.1124	0.0102	0.3940	0.0219	0.0183	0.1140	0.0349	0.4680
Oosthuizen [18]	0.0054	0.0042	0.0146	0.0515	0.2990	0.0196	0.0070	0.0188	0.0257	0.3490
Gupta [22]	0.0090	0.0029	0.0240	0.0092	0.3010	0.0065	0.0064	0.0210	0.0090	0.2920
Al-Arabi and Khamis [20]	0.0684	0.0558	0.1584	0.0920	0.0159	0.1000	0.0519	0.1539	0.1289	0.0194
Present correlation (16)	0.0066	0.0211	0.0500	0.0366	0.1123	0.0121	0.01662	0.0397	0.0645	0.1384
Present correlation (17)	0.1724	0.1632	0.4680	0.2698	0.7670	0.1937	0.1672	0.4640	0.2843	0.8748
Present correlation (18)	0.0466	0.0683	0.1955	0.0443	0.0607	0.0450	0.0593	0.1778	0.0164	0.0732
Present correlation (19)	0.0069	0.0073	0.0066	0.0250	0.3670	0.0092	0.0081	0.0182	0.0487	0.3220

TABLE V
MEAN RELATIVE QUADRATIC ERROR FOR ANGLE OF INCLINATION θ = 75°

Experimental Data→ Correlations ↓	Bansal [23]	Muhhadin [17]	Al-Arabi and Khamis [20]
Bansal [23]	0.0042	0.0048	0.0360
Oosthuizen [18]	0.0306	0.0084	0.0347
Muhaddin [17]	0.0117	0.0041	0.0803
Al-Arabi and Khamis [20]	0.0989	0.0396	0.1393
Present correlation (16)	0.0374	0.0182	0.0338
Present correlation (17)	0.2045	0.1670	0.4241
Present correlation (18)	0.0176	0.0450	0.1571
Present correlation (19)	0.0288	0.0140	0.0251

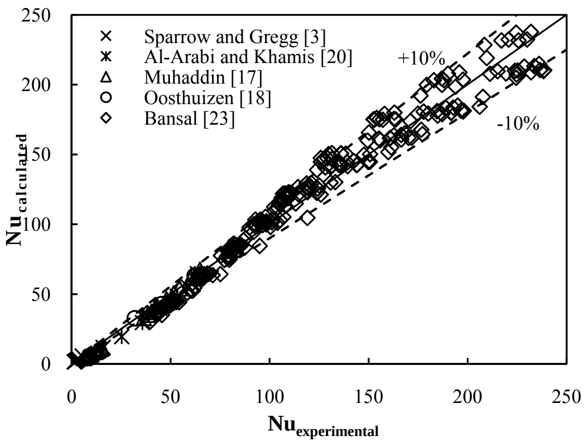

Fig. 5 Comparison of (19) with experimental data for heat transfer from vertical cylinders

TABLE VI
MEAN RELATIVE QUADRATIC ERROR FOR ANGLE OF INCLINATION θ = 90°

Experimental Data→ Correlations ↓	Bansal [23]	Muhhadin [17]	Oosthuizen [18]	Sparrow and Gregg [3]	Nagendra et al. [6]	Al-Arabi and Khamis [20]
Bansal [23]	0.0075	0.0293	0.0866	0.1531	0.1124	0.0147
Oosthuizen [18]	0.0096	0.0032	0.0474	0.1194	0.3442	0.0217
Muhaddin [17]	0.0088	0.0109	0.0571	0.1294	0.3372	0.0139
Al-Arabi and Khamis [20]	0.0098	0.0050	0.0494	0.1216	0.1453	0.0198
Nagendra et al. [6]	0.0488	0.2389	0.4496	0.2870	0.5917	0.3158
Present correlation (16)	0.0055	0.0151	0.0300	0.1125	0.1224	0.0656
Present correlation (17)	0.0086	0.0892	0.1980	0.2314	0.0444	0.0832
Present correlation (18)	0.0063	0.0399	0.0625	0.1833	0.1807	0.1069
Present correlation (19)	0.0054	0.0204	0.0295	0.0099	0.3500	0.0700

For the case of vertical cylinders (θ = 90°), the correlations of Bansal [23], Oostuizen [18], Muhhadin [17], Al-Arabi and Khamis [20] and Nagendra et al. [6] were tested. Table VI gives the calculated values of mean relative quadratic error in case of cylinders inclined at an angle of 90°. It is observed that minimum discrepancy between observed and calculated values is shown by (19) with the data of Bansal [23], Oosthuizen [18] and Sparrow and Gregg [3]. In this case the experimental data of Nagendra et al. [6] is best represented by the correlation of Bansal [23], and that of Muhhadin [17] is well represented by correlation of Oosthuizen [18] with minimum error. It is evident from Fig. 5 that (19) predicts the entire available experimental data available within ±10% except for the data of Al-Arabi and Khamis [20].

It stands justified to say that although (19) gives higher values of MRQE in some cases, still it predicts the heat transfer data of different researchers well within ±10%. The only one and most prominent exception is the data of Al-Arabi and Khamis [20]. But it must be observed that all the available correlations fail to correlate this data within the reasonable error. This may be due to the fact that Al-Arabi and Khamis [20] have calculated Nu and Gr based on the length of the cylinder as the characteristic dimension for all horizontal, vertical and inclined cylinders. As it has been said earlier, for horizontal cylinders, as the gravity force acts in the radial direction, the dimension characterizing the heat transfer should be the diameter of the cylinder. But Al-Arabi and Khamis [20] have exceptionally taken the length of the cylinder as the characterizing dimension. Since for vertical cylinders, the characterizing dimension should be the length of the cylinder, all the correlations give error within ±10 to ±15% with their data. Equation (17) fails to predict the data due to the fact that natural convection boundary layers are not thin for cylindrical surfaces and it is seen that the thermal boundary layer around a circular cylinder is nearly 30% of the cylinder diameter and for such thick boundary layers, curvature effects are important. Since we are considering natural convection in laminar regime only, (18) fails to predict the data since exponent 1/3 has been specified for turbulent regime by various researchers as given in the literature. Equation (16) was found to predict the available experimental data to within ±20% for all cylinder inclinations ($0° \leq \theta \leq 90°$).

VII. Conclusion

We can conclude from the above discussion that present correlation (19) is a unified equation which can be applied to predict the natural convection heat transfer from all horizontal, vertical and inclined cylinders. The accuracy of the predicted data would lie within ±10%. This correlation is simple to apply in comparison with the other correlations available in literature. Although the correlation given by Bansal [23] is also a simple and unified correlation, but the deviation between experimental and predicted values with this correlation is greater than 20% for vertical cylinders which is almost double the value given by present proposed correlation (19). Applicable range for this correlation is $1.4\times10^4<Gr<1.2\times10^{10}$ and $0.68<Pr<0.72$.

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