Error Analysis of Friction Factor Formulae with Respect to Colebrook-White Equation

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Abstract: ***An important and integral part of pressure drop in a pipe involves the determination of friction factor. The Darcy–Weisbach friction factor formula is used for calculation of pressure loss in pipes. The Colebrook–White (C-W) equation gives the best approximation to Darcy – Weisbach friction factor for turbulent flow. C-W equation cannot be solved directly due to its implicit form. Several numbers of approximate explicit equations have been proposed by many investigators. A brief review on friction factor formulae is presented. The study is to select a suitable friction factor formula in order to use it in pipe flow study for the calculation of friction factor. Thus an analysis is done to compare the percentage error of friction factor correlations. Based on applicability range of Reynolds number and pipe roughness, few equations are chosen. Relative percentage error of these selected approximate resistance equations are evaluated against the full range of flow conditions at different roughness sizes and found that average percentage error by Fang's(2011) and Romeo's(2008) equations are quite low in comparison to the others. Moreover it gives significantly better result than the commonly used equation of Barr (1981).Thus field engineer may use any one of the above explicit equations in the computation of friction factor value.***

Keywords: Colebrook-White, explicit approximations, friction factor formula, error analysis.

1. Introduction

Pipe flow under pressure is used for a lot of purposes. Therefore it has become necessary to select a correct resistance equation for friction factor evaluation. The various C-W explicit approximations taken are: Barr (1981), Zigrang-Sylvester (1982), Halland (1983), Romeo (2002), Brkic (2011) and Fang (2011). Comparative error analysis is made to assess the validity in using these six equations to evaluate friction factor values. Full range of Reynolds numbers from 2.5 x 10^3 to 10^7 are taken to cover the turbulent flow stage up to fully turbulent. Relative roughness [k/D] values are also changed from 10^{-7} to 10^{-2}. Friction factor values by these six equations and C-W equation for above flow stages and roughness are calculated. Percentage error is calculated by comparing the friction factor of selected equations to that of friction factor by C-W equation using the following equation:

Percentage error

$$= \frac{(\text{friction factor of explicit equation}) - (\text{friction factor by C-W})}{(\text{friction factor by C-W})} \times 100$$

2. Reviews on Friction Factor Formula

The Darcy-Weisbach friction factor is used to assess the resistance of flow that is
expressed as:

$$\frac{1}{\sqrt{f}} = \frac{V}{\sqrt{sgD}} \qquad (1)$$

Equation (1) does not consider overtly the roughness and viscosity of the liquid. To obtain a more general formula which considers these two parameters explicitly, recourse has to be made to a more modern concept. Prandtl (1932) had deduced a formula for friction factor „f" in smooth pipe as a function of Reynolds number „R". In a smooth pipe flow, the viscous sub-layer completely submerges the effect of average roughness of the pipe „k" on the flow. In this case, f is a function of Reynolds"s number R and is independent of the effect of „k" on the flow.

In 1933, Nikuradse verified the Prandtl"s boundary layer theory and proposed the universal resistance equation for fully developed turbulent flow in smooth pipe with empirical constants 2 and 2.51, where pipe diameter is considered as uniform and is expressed as:

$$\frac{1}{\sqrt{f_{smooth}}} = 2\log_{10}\left[\frac{R\sqrt{f}}{2.51}\right] \qquad (2)$$

In case of rough pipe flow, the viscous sub-layer thickness is very small when compared to roughness height and thus the flow is dominated by the roughness of the pipe and hence f becomes independent of R and depends only on relative roughness values. Nikuradse evaluated a formula for f in terms of ratio of diameter D of the pipe to the diameter size k of the sand grains that he had used to roughen the inside of the pipe. The formula is re-arranged as:

$$\frac{1}{\sqrt{f_{rough}}} = 2\log_{10}\left[\frac{2.71D}{k}\right] \qquad (3)$$

Nikuradse"s data have been served as the basis for many subsequent analysis of frictional resistance in pipes and in open channels for smooth, transitional and fully rough turbulent flow. However, Nikuradse used uniform sand grains for roughness which produced an increase in f with Reynolds"s number R over a particular range of partly rough flow. In 1937, Colebrook and White investigated the same range using non-uniform roughness. It was found that f is decreased throughout the partly rough flow regions. In 1939, combining equations (2) and (3), Colebrook gave the following friction factor formula for commercial pipe

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left[\frac{k}{3.71\mathrm{D}} + \frac{2.51}{R\sqrt{f}}\right] \qquad (4)$$

where, k/D is the relative pipe roughness which is the ratio of the mean height of roughness of the pipe to the pipe diameter. Thus the equation (4) is called Colebrook-White (C-W) transition formula for smooth to rough turbulent flow, and is one of the important and popular formulae in resistance to flow in pipes. The equation can be solved by trial and error methods. White gave approximations to the logarithmic smooth turbulent element in the Colebrook White functions which was compatible in form with the original, if Reynolds number to an index is accepted as a substitute for $R\sqrt{f}$

$$\frac{1}{\sqrt{f}} \sim 1.8\log_{10}\left(\frac{R}{6.8}\right) = 2\log_{10}\left(\frac{R^{0.9}}{5.614}\right) \qquad (5)$$

This is one of the important and popular formulae in resistance of flow in pipes.

Explicit approximations for Colebrook-White equations are shown in tabular form as:

Table 1: Explicit approximation for Colebrook-White equation

Sl. no	*Authors*	*Mathematical expression*	*Applicability range*
1	Moody equation: *(1944)*	$f = 0.0055\left[1 + \left\{2000(k/D) + \frac{10^6}{R}\right\}^{\frac{1}{3}}\right]$	R = 4000 – 5×10^8^ k = 0 – 0.01
2	Altshul equation: *(1966)*	$f = 0.11\left(\frac{68}{R} + \left({}^{k}/_{D}\right)\right)^{0.25}$	not specified
3	Wood equation: *(1966)*	$f = a + bR^{-c}$ where $a = 0.53\left(\frac{k}{D}\right) + 0.094\left(\frac{k}{D}\right)^{0.225}$ $b = 88\left(\frac{k}{D}\right)^{0.44}$ $c = 1.62\left(\frac{k}{D}\right)^{0.134}$	R= 4000 – 5 × 10^7 $\frac{k}{\mathrm{D}}$ = 0.00001 – 0.04
4	Churchill equation: *(1973)*	$f = \left[8\left(\frac{8}{R}\right)^{12} + (A+B)^{\frac{-3}{2}}\right]^{\frac{1}{12}}$, where $A = \left[-2\log_{10}\frac{k}{3.7D} + \left(\frac{0.7}{R}\right)^{0.9}\right]^{16}$ $B = \left(\frac{37530}{R}\right)^{16}$	not specified
5	Eck equation: *(1973)*	$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{k}{3.71D} + \frac{15}{R^{0.9}}\right)$	not specified
6	Swamee-Jain equations : *(1976)*	$\frac{1}{\sqrt{f}} = 1.14 - \left[2\log_{10}\left(\frac{k}{D} - \frac{21.25}{R^{0.9}}\right)\right]$	R= 5000 – 10^8 $\frac{k}{\mathrm{D}}$ = 0.000001 – 0.05
7	Chen equation: *(1979)*	$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{k}{3.7065D} - \frac{5.0452A}{R}\right)$ Where, $A = \left[\left(\frac{\left(\frac{k}{D}\right)^{1.1098}}{2.8257}\right) - \left(\frac{5.8506}{R^{0.8981}}\right)\right]$	R = 400 – 4 × 10^8 $\frac{k}{\mathrm{D}}$ = not specified
8.	Round equation: *(1980)*	$f = \left[-1.8\log\left(0.135\left(\frac{k}{D}\right) + \frac{6.5}{R}\right)\right]^{-2}$	R= 4000 – 4 × 10^8 $\frac{k}{\mathrm{D}}$ = 0 – 0.05
9.	Shacham equation: *(1980)*	$f = \left[-2\log_{10}\left(\left(\frac{k}{3.7D}\right) - \frac{5.02}{R}\log_{10}\left(\left(\frac{k}{3.7D}\right) + \frac{14.5}{R}\right)\right)\right]^{-2}$	not specified
10.	Barr equation 1981	$\frac{1}{\sqrt{f}} = -2\log_{10}\left[\frac{K}{3.7D} + \frac{5.1286}{R^{0.89}}\right]$	not specified
11.	Zigrang-Sylvester equation :*(1982)*	$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{k}{3.7065D} + \frac{5.02A}{R}\right)$ Where, $\mathrm{A} = \log_{10}\left(\frac{k}{3.7065D} + \frac{5.02B}{R}\right)$ $\mathrm{B} = \log_{10}\left(\frac{\epsilon}{3.7065D} + \frac{13}{R}\right)$	R= 2300 – 10^8 $\frac{k}{\mathrm{D}}$ = 0.000004 – 0.05
12.	Halland equation: *(1983)*	$\frac{1}{\sqrt{f}} = -1.8\log_{10}\left[\left(\frac{k}{3.7D}\right)^{1.11} + \frac{6.9}{R}\right]$	R= 2300 – 10^8 $\frac{k}{\mathrm{D}}$ = 0.000001 – 0.05
13.	Tsal equation: *(1989)*	$f = \begin{cases} C & if\ (C \geq 0 \\ 0.0028 + 0.85C & if\ (C < \end{cases}$ $C = 0.11\left(\frac{68}{R} + \frac{k}{D}\right)^{0.25}$	R= 4000 – 10^8 $\frac{k}{\mathrm{D}}$ = 0 – 0.05
14	Manadilli correlation:(1997)	$f = \left[-2\log\left(\frac{k}{3.70} + \frac{95}{R^{0.983}} - \frac{96.82}{R}\right)\right]^{-2}$	R= 4000 – 10^8 $\frac{k}{\mathrm{D}}$ = 0 – 0.05
15.	Monzon-Romeo-royo equation: *(2002)*	$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{k}{3.7065D} + \frac{5.0272B}{R}\right)$ $\mathrm{B} = \log_{10}\left(\frac{k}{3.827D} + \frac{4.567A}{R}\right)$ $A = \log_{10}\left[\left(\frac{k}{7.7918D}\right)^{0.9924} + \left(\frac{5.3326}{208.815 + R}\right)^{0.9345}\right]$	R = 2000 – 1.5×10^8 $\frac{k}{\mathrm{D}}$ = not specified
17.	Goudar - Sonnad equation: *(2008)*	$\frac{1}{\sqrt{f}} = a\left[\ln\left(\frac{d}{q}\right) + \delta_{CFA}\right]$ Where, $a = \frac{2}{\ln(10)}$ $b = \frac{K/D}{\ln(10)}$ $d = \frac{\ln(10)}{5.02R}$ $s = bd + \ln(d)$ $q = S^{\left(\frac{s}{s+1}\right)}$ $g = bd + \ln\left(\frac{d}{q}\right)$	Not specified

		$z = \ln\left(\frac{q}{g}\right)$ $\delta_{CFA} = \delta_{LA}\left(1 + \frac{\frac{z}{2}}{(g+1)^2} + \frac{1}{\frac{z}{3}(2g-1)}\right)$ $\delta_{LA} = \frac{g}{(g+1)} z$	
18.	Avci and Karagoz correlation:(*2009*)	$f = \frac{6.4}{\left[\ln R - \ln\left(1 + 0.01R\frac{K}{D}\left(1 + 10 \times\right.\right.\right.}$	Not specified
19	Papaevangelou correlation:(*2010*)	$f = \frac{0.2479 - 0.0000947(7 - \log R)^4}{\left(\log\left(\frac{K}{3.615D} + \frac{7.366}{R^{0.9142}}\right)\right)^2}$	Not specified
20.	Brkic correlation:(*2011*)	$f = \left[-2\log\left(\left(\frac{2.18S}{R}\right) + \left(\frac{K}{3.71D}\right)\right)\right]^{-2}$ $S = \ln\frac{R}{1.816\ln\left(\frac{1.1R}{\ln(1+1.1R)}\right)}$	Not specified
21.	Fang equation: (*2011*)	$f = 1.613\left[\ln(0.234\left(\frac{K}{D}\right)^{1.1007} - \frac{60.525}{R^{1.1105}} + \frac{56.291}{R^{1.0712}}\right]^{-2}$	R= 2000 – 10^8
22.	Ghanbari – Farshad–Rieke"s equation: (*2011*)	$f = \left[-1.521 \times \log\left(\left(\frac{K/D}{7.21}\right)^{1.042}\right) + \left(\frac{2.731}{R}\right)^{0.9152}\right]^{-2.169}$	Not specified

Frictiona factor plays an important role (Medhi Das and Sarma 2016, Medhi Das et al.2016, Medhi Das et al.2017) in unsteady flow equations.

3. Results and Analysis

The results of the Numerical percentage error of explicit C-W equations are shown in different figures for full range of flow conditions at different roughness sizes. The results are also shown in tabular form only for roughness size, k/D = 10^{-7} just as illustration.

Numerical percentage error assessment of C-W equations:

Table 2: Values of friction factor for the following formulae, when k/D = 10^{-7}

Reynolds No.	k/D	Barr	Fang	Romeo	Brk ic	Halland	Zigrang Sylvester	C-W
2500	1E-07	0.04668	0.04612	0.04612	0.04636	0.04713	0.04612	0.04605
4000	1E-07	0.04013	0.03999	0.03997	0.04015	0.04042	0.03992	0.03991
6000	1E-07	0.03553	0.03559	0.03555	0.0357	0.03573	0.0355	0.0355
8000	1E-07	0.03273	0.03288	0.03283	0.03296	0.03287	0.03277	0.03279
10000	1E-07	0.03078	0.03097	0.03093	0.03103	0.03089	0.03086	0.03088
30000	1E-07	0.02331	0.02356	0.02351	0.02358	0.02332	0.02346	0.02348
50000	1E-07	0.02074	0.02096	0.02092	0.02097	0.02071	0.02087	0.02089
80000	1E-07	0.01873	0.01892	0.01888	0.01892	0.01869	0.01884	0.01886
100000	1E-07	0.01787	0.01805	0.01801	0.01805	0.01783	0.01797	0.01799
300000	1E-07	0.01442	0.01451	0.01448	0.0145	0.01435	0.01445	0.01446
700000	1E-07	0.01239	0.01243	0.0124	0.01242	0.01232	0.01238	0.01239
1000000	1E-07	0.01167	0.01169	0.01166	0.01167	0.01159	0.01164	0.01165
3000000	1E-07	0.00979	0.00976	0.00973	0.00974	0.00971	0.00972	0.00973
7000000	1E-07	0.00864	0.00858	0.00855	0.00856	0.00856	0.00854	0.00855
10000000	1E-07	0.00822	0.00814	0.00812	0.00813	0.00814	0.00811	0.00811

Table 3: Percentage error in the formulae, when k/D = 10^{-7}

Reynolds No.	k/D	Barr	Fang	Romeo	Brkic	Halland	Zigrang-Sylvester	C-W
2500	1E-07	0.046682	0.046117	0.046119	0.046359	0.047129	0.046118	0.04605
4000	1E-07	0.040134	0.039993	0.039965	0.040145	0.040423	0.039921	0.03991
6000	1E-07	0.035531	0.035594	0.035554	0.035697	0.035725	0.035496	0.0355
8000	1E-07	0.03273	0.032879	0.032834	0.032956	0.032871	0.032772	0.03279
10000	1E-07	0.030779	0.030972	0.030925	0.031034	0.030886	0.030863	0.03088
30000	1E-07	0.023314	0.023557	0.023511	0.023576	0.023317	0.023458	0.02348
50000	1E-07	0.020738	0.020958	0.020915	0.020967	0.020714	0.020868	0.02089
80000	1E-07	0.018727	0.018917	0.018877	0.018919	0.018685	0.018836	0.01886
100000	1E-07	0.017874	0.018048	0.018009	0.018048	0.017825	0.01797	0.01799
300000	1E-07	0.014415	0.014511	0.014478	0.014503	0.014347	0.014449	0.01446
700000	1E-07	0.012391	0.012433	0.012403	0.012421	0.012316	0.01238	0.01239
1000000	1E-07	0.011665	0.011687	0.011657	0.011673	0.011588	0.011637	0.01165
3000000	1E-07	0.00979	0.00976	0.009733	0.009744	0.009711	0.009718	0.00973
7000000	1E-07	0.008639	0.008577	0.008553	0.008562	0.008561	0.008541	0.00855
10000000	1E-07	0.008216	0.008142	0.00812	0.008128	0.008137	0.008108	0.00811
	Average	-0.10052	-0.299394	0.108434	0.364616	0.034508	0.061888	

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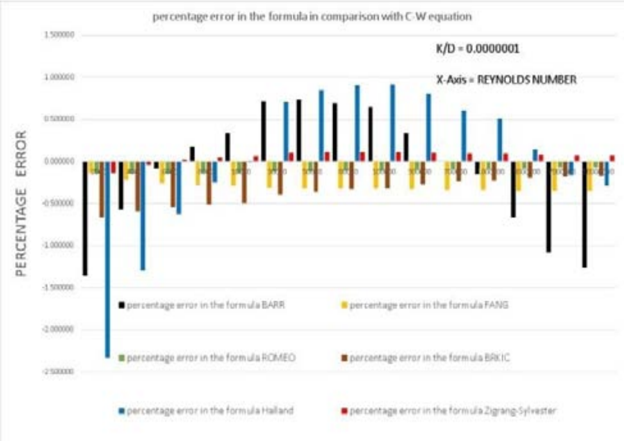

Figure 1: Percentage error in different formulae, when k/D=10^{-7}

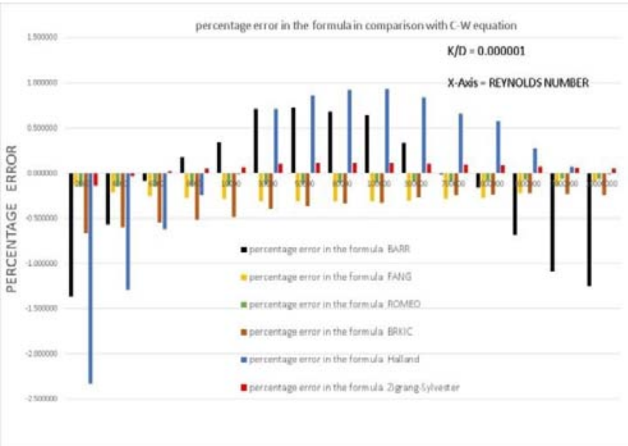

Figure 2: Percentage error in different formulae, when k/D=10^{-6}

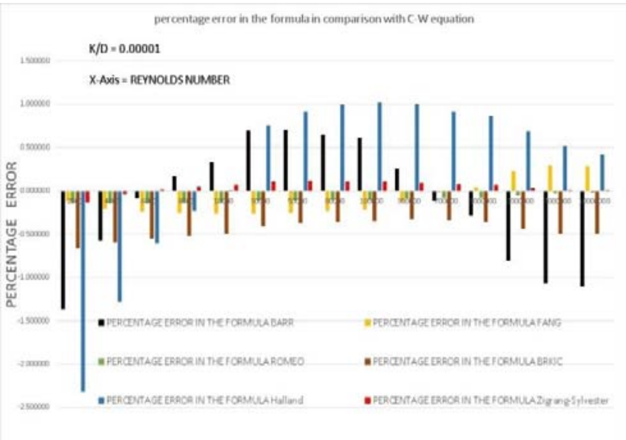

Figure 3: Percentage error in different formulae, when k/D=10^{-5}

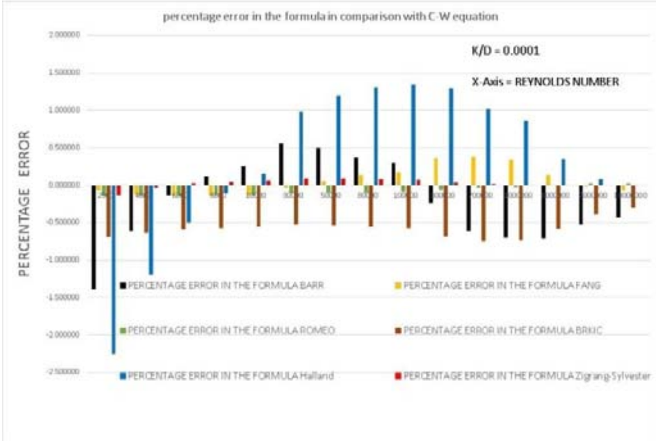

Figure 4: Percentage error in different formulae, when k/D=10^{-4}

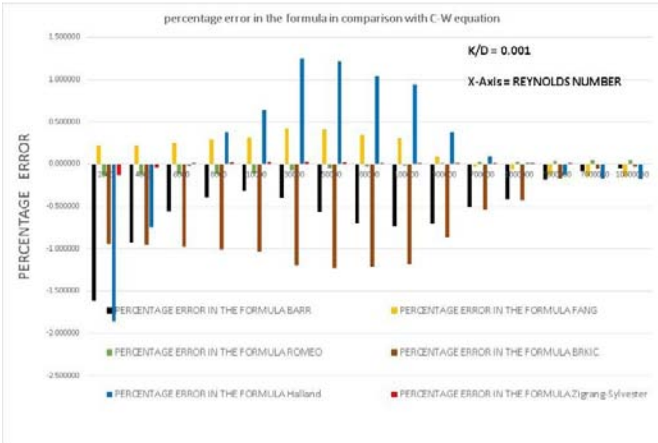

Figure 5: Percentage error in different formulae, when k/D =10^{-3}

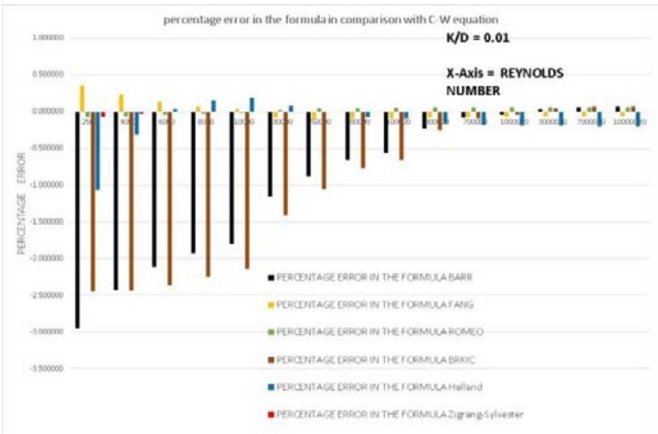

Figure 6: Percentage error in different formulae, when k/D=10^{-2}

Table 4: Average error in the six explicit C-W equations

k/D	*Barr*	*Fang*	*Romeo*	*Brkic*	*Halland*	*Zigrang-Sylvester*
0.0000001	-0.10052	-0.299394	-0.108434	-0.364616	0.034508	0.061888
0.000001	-0.105363	-0.246744	-0.107266	-0.377924	0.090032	0.058931
0.00001	-0.130959	-0.091019	-0.099144	-0.451249	0.244014	0.045695
0.0001	-0.217922	0.054697	-0.077246	-0.577767	0.30189	0.023145
0.001	-0.544801	0.156527	-0.039684	-0.789613	0.190453	-0.003428
0.01	-0.974974	0.003024	0.018762	-1.047591	-0.147902	-0.007906
AVERAGE	-0.345757	-0.070485	-0.068835	-0.60146	0.118832	0.189118

Table 2 shows the values of friction factor of the selected explicit equations for all Reynolds numbers when k/D is 0.0000001. Table 3 shows the percentage errors in the formulae. Figure 1 to 6 shows percentage error in different formulae in comparison with C-W equation for all Reynolds numbers and roughness sizes.Table 4 shows the average error in all k/D and Reynolds numbers in the six equations. Best results are obtained from Fang‟s and Romeo‟s equations with least percentage error.

4. Conclusion

The Colebrook-White equation is still the best equation that provides a relation between the friction factor, Reynolds number and relative roughness. Its only disadvantage is the implicit form of the equation. Barr (1981) modified C-W equation to determine friction factor. Review of the resistance equations shows that, many researchers have reported their explicit approximations of C-W equation. Some of them did not mention the ranges of Reynolds number and relative roughness. Some of them are presented complicated equations. Barr‟s (1981) explicit solution of C-W equation is always preferred to evaluate friction factor. This is due to its simplicity, reliability and involvement of lesser percentage of error. Thus an analysis is made on six such explicit solutions based on full ranges of Reynolds number and relative roughness. The average percentage error of Fang (= - 0.070485) and Romeo (= - 0.068835**)** was quite low in comparison to the other equations. Earlier many researchers preferred approximation equation of Barr (1981) to that of Halland (1983), Zigrang – Sylvester (1982) equations, even all were developed parallely. It was mainly due to less mathematical computation process in the Barr‟s equation, though the percentage errors of later ones are less.

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