CHAPTER IV
RESULTS AND DISCUSSION

4.1 Data Available

Data collection is the most crucial task in this research. An ANN model demands a large volume of data for training purposes and cross-validation in order to solve complex, nonlinear problems accurately. In addition, the accuracy of the correlation depends on the data used for developing correlation as well. The data employed in this research were carefully collected from the existing publications. The list of all the available data sources is shown in Table 4.1.

Table 4.1 List of all the available data sources

Sources	Relevant crude oil properties
Glaso (1980)	P_b, B_{ob}, R_s
Ostermann and Owolabi (1983)	P_b, B_{ob}, R_s
Al-Marhoun (1988)	P_b, B_{ob}, R_s
Abdul-Majeed et al. (1988)	B_{ob}, R_s
Abdul-Majeed et al. (1990)	R_s, μ_o
Dokla and Osman (1991)	P_b, B_{ob}, R_s
Labedi (1992)	μ_o
Omar and Todd (1993)	P_b, B_{ob}, R_s
De Ghetto and Villa (1994)	P_b, B_{ob}, μ_o, R_s
De Ghetto et al. (1995)	μ_o
Mahmood and Al-Marhoun (1996)	P_b, B_{ob}, R_s
Velarde et al. (1997)	P_b, B_{ob}, R_s
Gharbi and Elsharkawy (1997)	B_{ob}, R_s
Gharbi and Elsharkawy (1999)	P_b,
Wu and Rosenegger (1999)	P_b, B_{ob}
Isehunwa et al. (2006)	μ_o
Bello et al. (2008)	P_b, B_{ob}, R_s

Note: P_b = bubble point pressure (psia), B_{ob} = bubble point oil formation volume factor, R_s = solution gas oil ratio (scf/stb)

For P_b modeling, 764 data points with 3,820 measurements including reservoir temperature (T_{res}), solution gas oil ratio (R_s), gas specific gravity (γ_g), oil specific gravity (γ_o), oil API gravity (API), and bubble point pressure (P_b) in each data point were collected for this work. After removing all redundant data, the total of 757 data points with 3,785 measurements were employed for developing bubble point pressure model. The data were randomly divided into two sets. A set of 557 data points were used for developing correlation and ANN, and another set of 200 data points were used for testing the models. Table 4.2 presents the data summary for developing bubble point pressure models and Table 4.3 presents the data summary for testing bubble point pressure models.

In order to develop and test B_{ob} correlation and ANN, the total of 1,175 data points with 5,875 measurements were selected after the repeated data were removed. The crude oil data comprised reservoir temperature, solution gas oil ratio, gas specific gravity, oil specific gravity, oil API gravity and bubble point oil formation volume factor. Furthermore, the crude oil data were randomly classified into a set of 875 data points for developing B_{ob} models, and another set of 300 data points for testing B_{ob} models. The data summaries for developing and testing B_{ob} models are shown in Tables 4.4 and 4.5, respectively.

Table 4.2 Data summary for developing P_b models (557 points)

Properties	Min	Max	AVG	S.D.	Skewness	Kurtosis
R_s (scf/bbl)	8.61	3298.66	644.368	518.154	1.49876	2.81296
T_{res} (°F)	74	341.6	199.587	52.4055	-0.2168	-0.4695
γ_g	0.61	3.4445	1.13424	0.42862	1.60444	2.89109
API°	6	56.8	35.1157	8.32354	-1.056	1.58375
P_b (psia)	79	7127	1976.5	1409.72	0.81095	0.28586

Table 4.3 Data summary for testing P_b models (200 points)

Properties	Min.	Max.	AVG	S.D.	Skewness	Kurtosis
R_s (scf/bbl)	17.21	3020	657.41	528.524	1.43495	2.55253
T_{res} (°F)	80	334.4	204.357	51.8959	-0.2426	-0.1802
γ_g	0.61	2.98	1.16574	0.44579	1.63334	2.9683
API°	6.3	56.5	35.972	8.41313	-1.2479	2.17911
P_b psia	95	6641	1970.43	1438.43	0.72348	-0.0341

Table 4.4 Data summary for developing B_{ob} models (875 points)

Properties	Min.	Max.	Average	S.D.	Skewness	Kurtosis
R_s (scf/bbl)	0	3298.66	523.534	480.242	1.66484	3.57134
T_{res} (°F)	74	593.996	187.693	54.1197	0.47773	2.71979
γ_g	0.511	3.4445	1.01727	0.37987	2.08889	5.32879
API°	6	59.5	32.8496	10.0429	-0.5984	-0.341
B_{ob}	1.028	2.916	1.34781	0.28297	1.77547	4.47046

Table 4.5 Data summary for testing B_{ob} models (300 points)

Properties	Min.	Max.	Average	S.D.	Skewness	Kurtosis
R_s (scf/bbl)	0	3020	552.867	481.115	1.75751	4.27439
T_{res} (°F)	75.002	341.6	187.153	54.102	0.08627	-0.6121
γ_g	0.525	2.98	1.03774	0.3922	2.02137	4.72544
API°	6.3	56.8	33.2908	9.72234	-0.6421	0.19895
B_{ob}	1.028	2.903	1.36313	0.29277	2.15482	6.97319

With respect to R_s modeling, after removing redundant data, a total of 750 data points including 3,750 measurements including R_s, T_{res}, γ_g, API°, and B_{ob} for each data point were collected. Nevertheless, the entire data for R_s had resulted in high errors after being applied to some published correlations. Data filtering was required for these data sets. The data points with the majority of errors over 15% of the prediction resulted from the published correlations was removed as invalid data (Mohammadpoor et al., 2010). The correlations used in data filtering were from Standing (1947), Glaso (1980), Al-Marhoun (1988), Petrosky Jr. and Farshad (1993), and Hemmati and Kharrat (2007) as they gave reasonably good R^2 value for the entire data. Finally, 254 data points with 1,270 measurements were selected as valid data. The data were randomly divided into two sets. A set of 204 data points were used in developing correlations and ANN, and another set of 50 data points were used for testing the models. Table 4.6 and 4.7 summarize the data used in developing and testing R_s models, respectively.

Table 4.6 Data summary for developing R_s models (204 points)

Properties	Min	Max	Average	S.D.	Skewness	Kurtosis
T_{res} (°F)	74	306	177.3103	53.5355	0.25833	-0.3837
P_b (psia)	133	7127	2461.832	1313.61	0.6429	0.77613
R_s (scf/bbl)	39	2249	715.2556	421.813	0.86782	0.8676
γ_g	0.61	1.981	0.883494	0.18043	2.37246	10.1396
API°	10	56.5	35.52543	6.71268	-0.253	1.45365
γ_o	0.75266	0.9902	0.847988	0.03317	0.37677	1.38331

Table 4.7 Data summary for testing R_s models (50 points)

Properties	Min	Max	Average	S.D.	Skewness	Kurtosis
T_{res} (°F)	80	305.1	179.244	56.591	0.44137	-0.2745
P_b (psia)	179	6641	2318.816	1684.23	0.86365	0.39826
R_s (scf/bbl)	39	2191.33	693.0238	566.516	0.98737	0.30701
γ_g	0.612	1.517	0.91048	0.18985	0.94314	0.78646
API°	10.9	53	34.19725	9.04099	-0.1313	-0.0513
γ_o	0.771	0.93771	0.857017	0.04043	-0.1042	-0.7448

Regarding to μ_o modeling, after removing duplicated data, 525 data points with 3,150 measurements were collected. With high errors similar to the case of R_s modeling, data filtering was mandatory. 446 data points were used after being filtered with the methods presented by Beal (1946), Vazquez and Beggs (1980), Khan et al. (1987), Kartoatmodjo and Schmidt (1991), De Ghetto and Villa (1994), Petrosky and Farshad (1995), Hossain et al. (2005), Isehunwa et al. (2006), Sutton and Bergman (2006), and Abedini et al. (2010). Therefore, a set of 357 data points used for developing and another set of 89 data points used for testing the μ_o models were selected at random. The data summaries for developing and testing μ_o models are shown in Table 4.8 and 4.9.

Table 4.8 Data summary for developing μ_o models (357 points)

Properties	Min	Max	Average	S.D.	Skewness	Kurtosis
T_{res} (°F)	80.6	305.1	181.336	36.4153	0.29233	0.79745
P (psia)	242.22	7411.54	3947.64	1405.58	-0.14157	-0.3801
API°	6	56.8	27.3126	10.363	0.208	-0.61701
P_b (psia)	113.129	6613.82	2618.97	1391.1	0.30147	-0.44678
μ_{ob} (cp)	0.093	90.3	4.78695	8.69585	4.13282	28.3054
μ_o (cp)	0.096	108.3	5.69268	10.76	4.31918	28.3166

Table 4.9 Data summary for testing μ_o models (89 points)

Properties	Min	Max	Average	S.D.	Skewness	Kurtosis
T_{res} (°F)	90.5	303.1	189.544	46.8272	0.53159	0.38161
P (psia)	351	7137.42	3845.11	1523.88	-0.09841	-0.66949
API°	7.9	51	27.8787	10.4373	0.03522	-0.74797
P_b (psia)	113.129	6272.98	2739.01	1603.7	0.25018	-0.66949
μ_{ob} (cp)	0.093	80.6	5.08887	12.1685	4.53219	22.8862
μ_o (cp)	0.099	86.6	6.18115	14.4356	4.0129	17.2185

4.2 Developed Correlations

The prepared data sets, presented in section 4.1 were used for developing new correlations for predicting each crude oil property by utilizing Minitab 16. A nonlinear regression was a technique used to create the correlations for the determination of each crude oil property using field parameters.

4.2.1 Bubble Point Pressure Correlation

After numerous trials using nonlinear regression technique in Minitab 16, the following equation was created to predict bubble point pressure:

$$P_b = 577.747(R_s^{0.444689} - 4.43941)e^{(0.00252849T_{res} - 0.0217755API - 0.976346\gamma_g)} \quad (4.1)$$

Equation 4.1 was modified from Calhoun's correlation form (Calhoun, 1976) with the changes in coefficients. It is a function of R_s, T_{res}, API, and γ_g. Residual plots of P_b obtained from Equation 4.1 are shown in Figure 4.1.

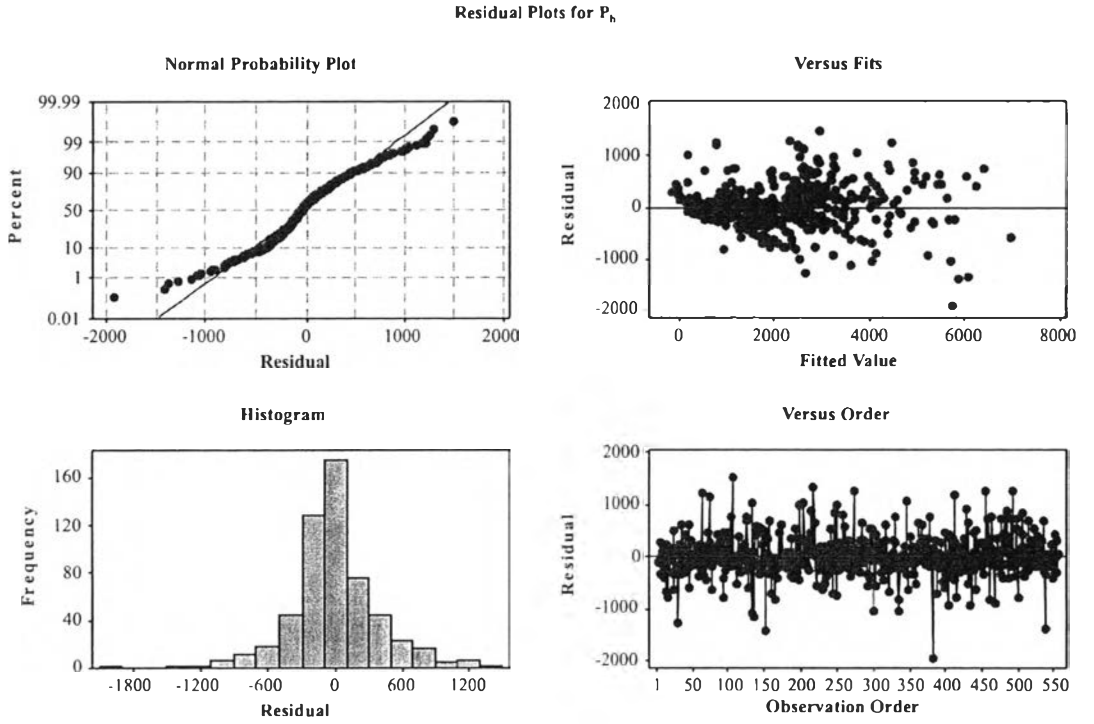

Figure 4.1 Residual plots resulted from developing P_b correlation using nonlinear regression technique.

4.2.2 Bubble Point Oil Formation Volume Factor Correlation

The B_{ob} expression in Equation 4.2 was developed from the data used in this work by using nonlinear regression technique. The results indicated that B_{ob} expression was a function of R_s, T_{res}, γ_g, and γ_o. In addition, this equation was correlated by modifying Petrosky-Farshad's correlation form (Petrosky Jr. and Farshad, 1993).

$$B_{ob} = 4.25999 \times 10^{-5} \left(R_s^{0.601715} \cdot \left(\frac{\gamma_g}{\gamma_o}\right)^{1.47844} + 0.968331 \cdot T_{res}^{0.68077} \right)^{1.99881} + 1.00387 \quad (4.2)$$

Plus, residual plots of B_{ob} generated from Minitab resulting from developing Equation 4.2 are illustrated in Figure 4.2.

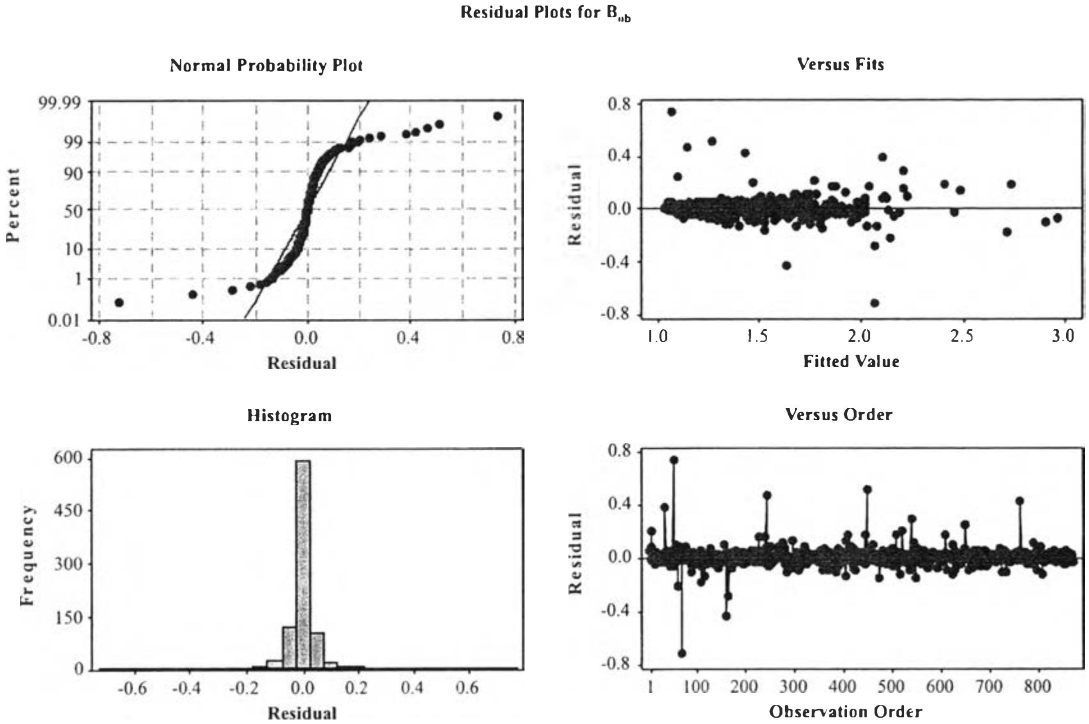

Figure 4.2 Residual plots resulted from developed B_{ob} correlation using nonlinear regression technique.

4.2.3 Solution Gas Oil Ratio Correlation

After numerous trials on nonlinear regression technique with respect to the available data, R_s correlation was correlated as a function of γ_g, P_b, γ_o, API, and T_{res}. Therefore, Equation 4.3 was developed for predicting R_s. The equation was modified from Frashad's correlation form (Frashad et al., 1996).

$$R_s = \frac{0.0395338\gamma_g P_b^{1.10041}}{(1-28.7354(\frac{\gamma_o}{T_{res}}))\times 10^{(0.0002.8594T_{res}-0.01575API)}} \qquad (4.3)$$

To examine the applicability of Equation 4.3, residual plots generated from developing R_s correlation are presented in Figure 4.3.

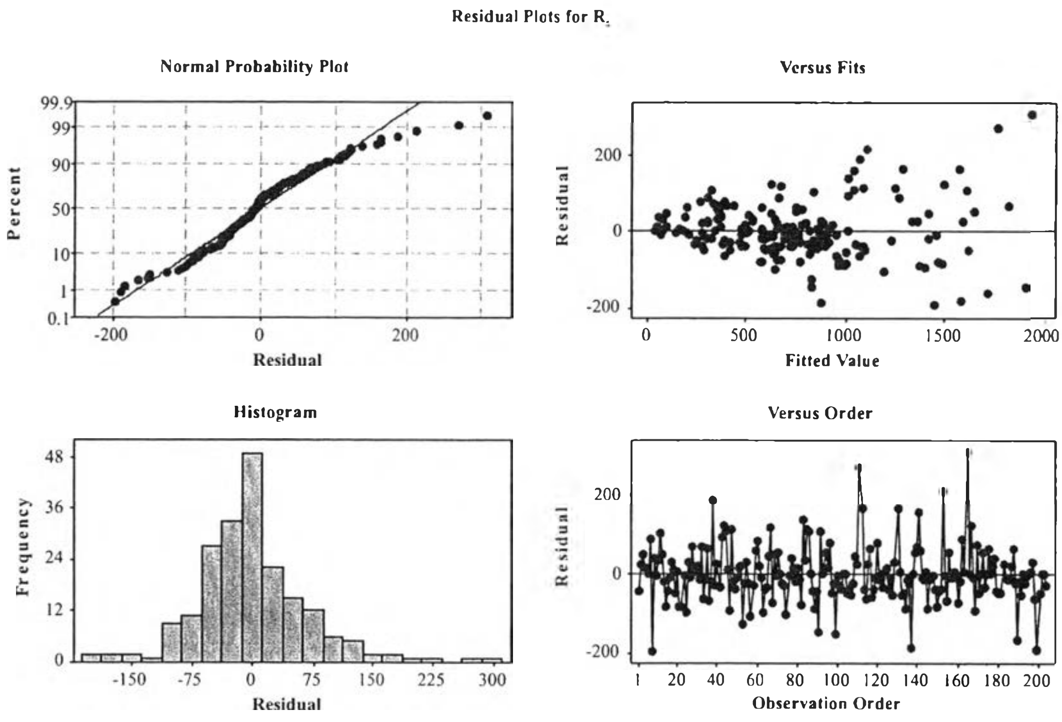

Figure 4.3 Residual plots resulted from developing R_s correlation from nonlinear regression technique.

4.2.4 Undersaturated Oil Viscosity Correlation

For μ_o correlation, after a number of trials, Equation 4.4 was exploited to predict μ_o as a function of oil viscosity at bubble point (μ_{ob}), T_{res}, reservoir pressure (P), and P_b.

$$\mu_o = \mu_{ob} + (1.16682\mu_{ob}^{1.0841052} - 0.474189) \cdot (P - P_b) \times 10^{-4} \quad (4.4)$$

Finally, the residual plots resulted from developing μ_o using Minitab are shown in Figure 4.4.

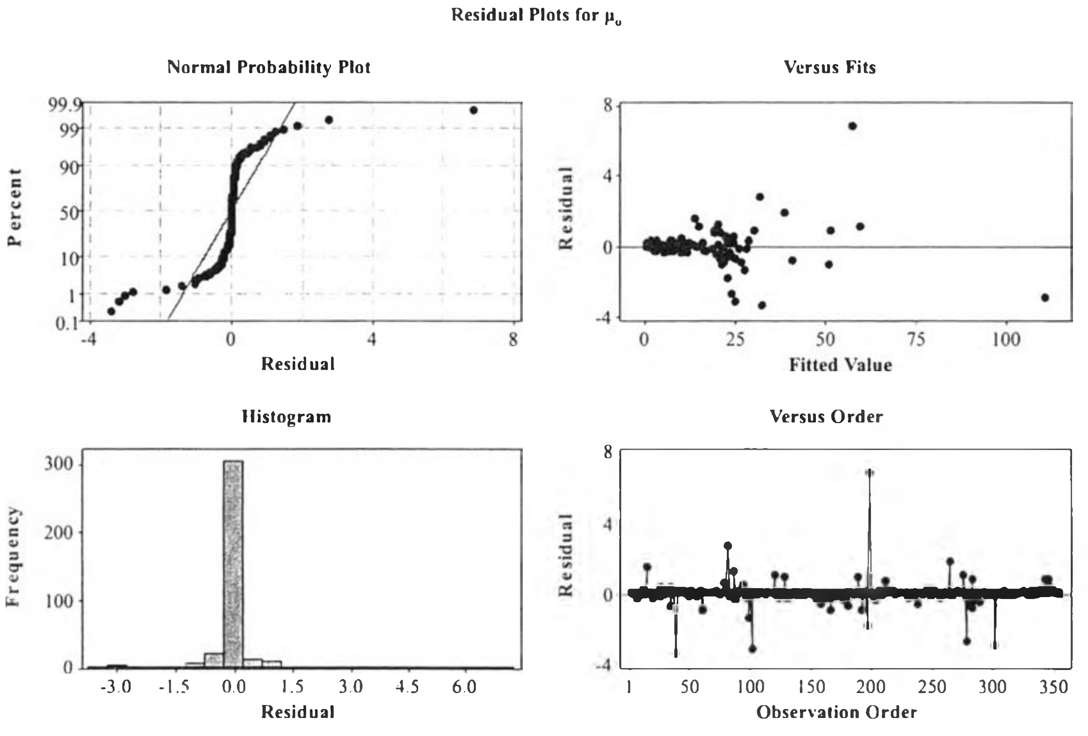

Figure 4.4 Residual plots for the developed μ_o correlation resulted from nonlinear regression technique.

4.3 Developed Artificial Neural Networks

Both developing correlations and ANN models employed the similar developing datasets (presented in section 4.1). Neural network toolbox (nntool), which is graphical user interface (GUI) embedded in Matlab was used to develop the ANN models. In this research, 70% of the developing data were randomly used for training, and 30% were used for validation and testing each network. Feed-forward, back-propagation neural network with one hidden-layer was applied to each model. Gradient descent with momentum (GDM) training algorithm and Levenberg-Marquardt (LM) learning algorithm were adopted in each model. Hyperbolic tangent sigmoid transfer function (Tansig) was used for the calculation between input layer and hidden layer, while linear transfer function (Purelin) was chosen to calculate the output from the hidden layer to the output layer.

4.3.1 Bubble Point Pressure Neural Network

From 557 data points out of the data set for developing P_b model (see section 4.1), 389 data points were randomly selected for training. 84 data points were also randomly selected for validation and another 84 data points were used for testing the network. Four input parameters including R_s, T_{res}, γ_g, and API were used as input parameters, while P_b is the target for the developing P_b ANN. After numerous trials, a neural network with 10 neurons in the hidden layer was recognized as the best model in training, validation, and testing the ANN. In other words, the 4-10-1 (i.e., input layer - hidden layer - output layer) neural network architecture was selected. The neural network architecture for the developed P_b ANN is illustrated in Figure 4.5.

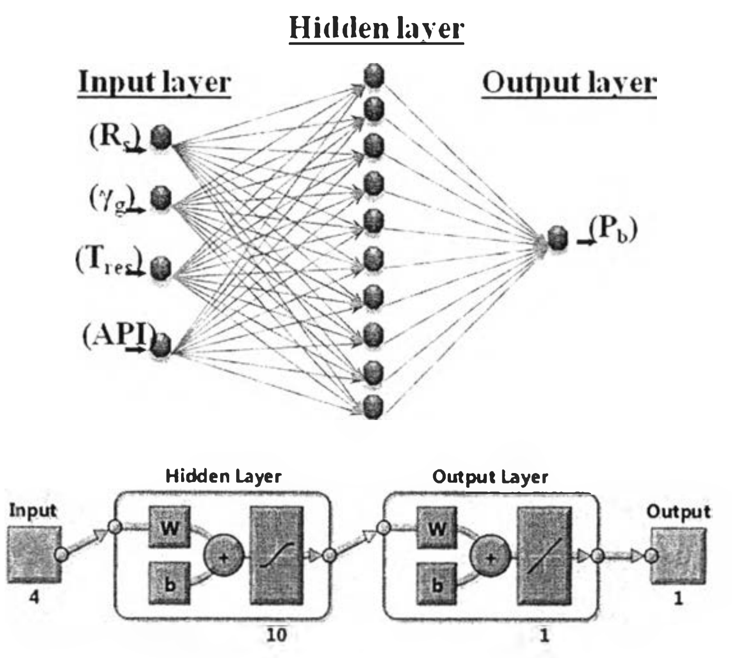

Figure 4.5 The architecture of the developed P_b ANN.

Regression plots resulted from the developed network outputs with respected to targets for training, validation, and testing the developing data set are shown in Figure 4.6. The regression plots gave reasonably good performance for all data sets with correlation coefficient (R value) above 0.96 for the total response in each case. Performance plots, shown in Figure 6.9, gave the best validation performance at iteration 14th with the mean square error (MSE) of 1,177,883.51. The training results, which are connection weight (W_{ji}) and bias (b_j) between each layer of P_b neural network, are shown in table 6.9.

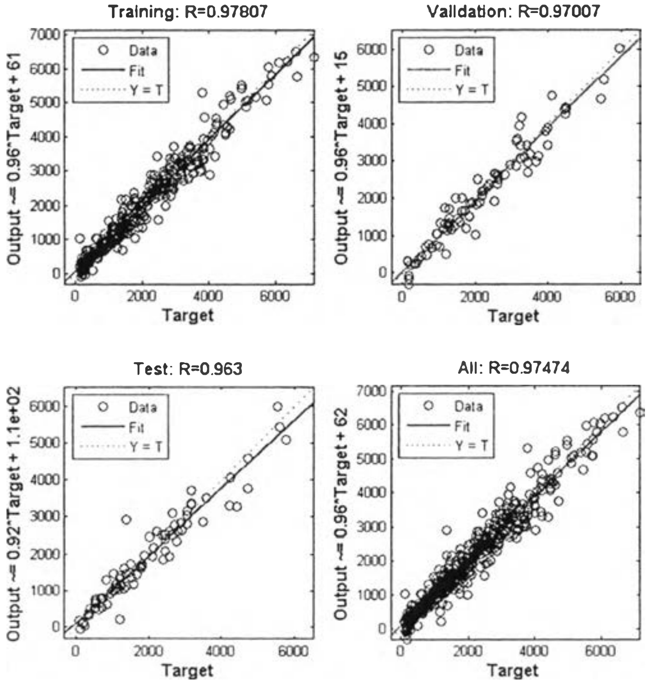

Figure 4.6 Regression plots of the P_b neural network outputs.

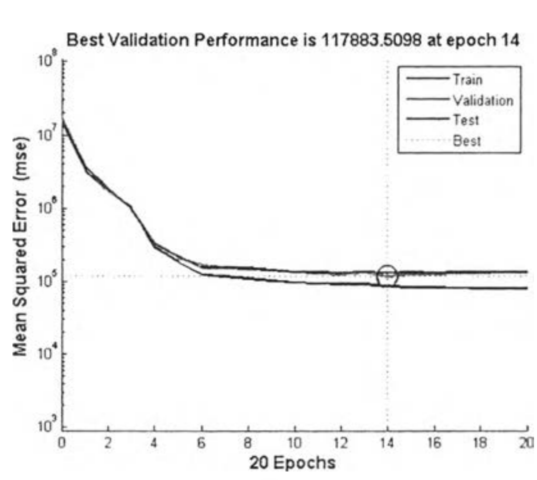

Figure 4.7 Performance plots of the developed P_b ANN.

Table 4.10 Connection weights and biases for the developed P_b neural network

	w_{ji}										b_j
j\i	1	2	3	4	5	6	7	8	9	10	
First layer											
1	-0.13712	-0.33441	1.4863	0.50169							2.1933
2	-1.4088	-4.6959	-2.4845	-0.1808							-0.10565
3	-2.2805	7.9196	-4.4596	1.5205							1.1446
4	-2.5518	-3.1182	-0.92311	4.5653							-1.0879
5	0.2058	2.061	2.8962	2.0211							-0.50916
6	2.8641	-0.86916	0.88196	4.2808							1.0816
7	-1.3071	-1.2768	1.4905	9.278							1.598
8	2.8033	-0.81956	-0.098831	-2.8951							3.615
9	6.5022	-0.73523	-0.087034	-2.4325							3.5421
10	2.0283	-0.0106	1.0566	0.41804							3.179
Second layer (output layer)											
1	-2.7849	-0.28332	0.053302	0.14211	-0.26872	-0.049906	-0.10666	0.085681	0.09737	1.1821	0.94689

4.3.2 Bubble Point Oil Formation Volume Factor Neural Network

In case of B_{ob} neural network model, four input parameters (i.e., R_s, T_{res}, γ_g, and γ_o) were used for B_{ob} prediction. From 875 data points used for developing the B_{ob} model (see section 4.1), 613 data points were employed for training purposes. 131 data points were selected randomly for validation and another 131 data points were assigned to test the neural network. After various iterations, the 4-12-1 neural network architecture was chosen for B_{ob} prediction as shown in Figure 4.8.

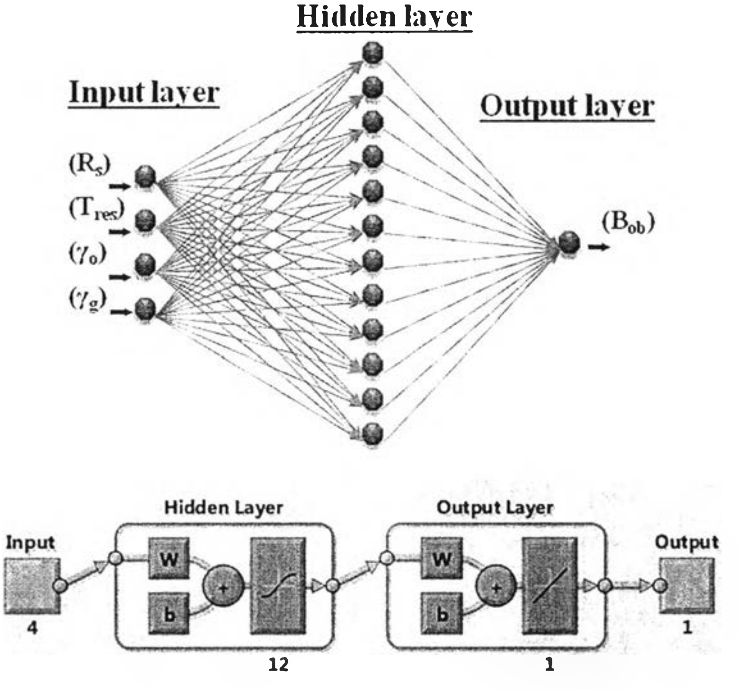

Figure 4.8 The architecture of the developed B_{ob} ANN.

Figure 4.9 presents the regression plots as a result of the outputs of the B_{ob} ANN comparing to the targets used for training, validation, and testing. The value of the MSE resulted from validation performance of the developed B_{ob} ANN is 0.0039261 at 4 epochs as depicted in Figure 4.10. Although, the MSE resulted from training the B_{ob} ANN is relatively low, the range of the B_{ob} value used in this work are generally in between 1.0 to 3.0. Moreover, the connection weights and biases, which are the results of the B_{ob} ANN are shown in table 4.11.

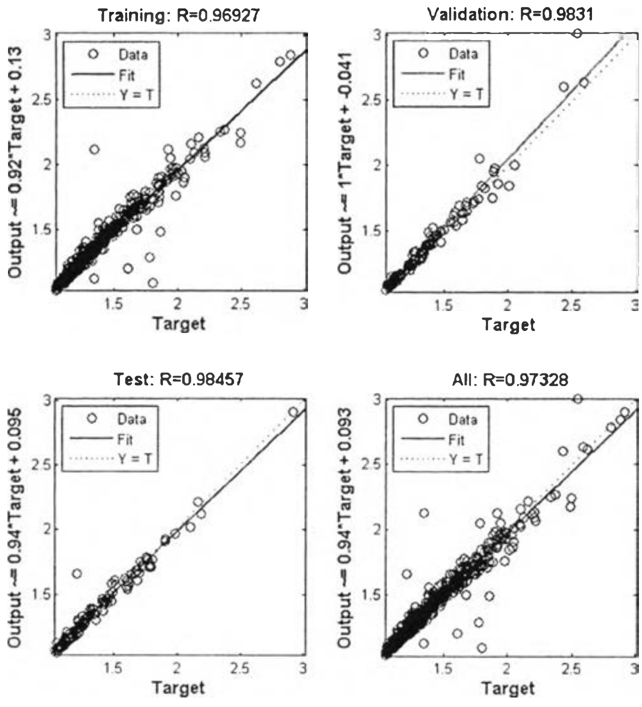

Figure 4.9 Regression plots of the B_{ob} ANN outputs.

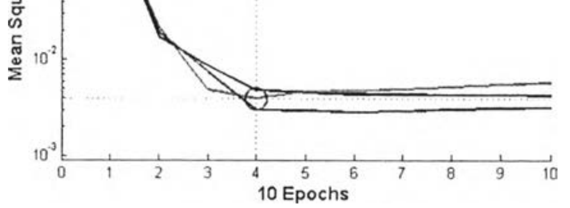

Figure 4.10 Performance plots of the developed B_{ob} ANN.

Table 4.11 Connection weights and biases for B_{ob} neural network model

	w_{ji}												b_j
j\i	1	2	3	4	5	6	7	8	9	10	11	12	
First layer													
1	-3.7885	-0.73268	-0.1973	-2.5793									4.3068
2	-1.578	3.0598	1.9243	-0.20581									3.8808
3	-1.6512	-0.53053	-1.2049	-0.7897									0.43339
4	0.74874	0.52802	0.1475	3.909									1.4545
5	2.243	0.42189	1.5931	0.53994									2.0292
6	0.36368	0.99081	-0.6465	-0.61309									0.32125
7	0.7214	-3.2948	0.22585	-0.54945									0.58692
8	-0.3878	-1.6791	-1.2342	1.4284									0.06498
9	2.1128	0.86987	-0.3278	1.0708									1.462
10	-1.2871	1.6473	1.6813	0.090412									-1.0217
11	-2.1487	-0.0099892	-0.323	-0.18022									-1.9552
12	1.0879	1.3284	-2.2623	0.4335									2.6979
Second layer (output layer)													
1	0.84657	0.01734	-1.5198	0.018101	0.12476	0.14344	-0.053519	0.047158	0.060627	-0.062205	-0.21342	0.28169	-0.32992

4.3.3 Solution Gas Oil Ratio Neural Network

For R_s neural network model, four input parameters, which are P_b, γ_g, API, and T_{res} were used. After numerous trials, a 4-11-1 neural network architecture (as shown in Figure 4.11) was selected to be the best model for determining R_s.

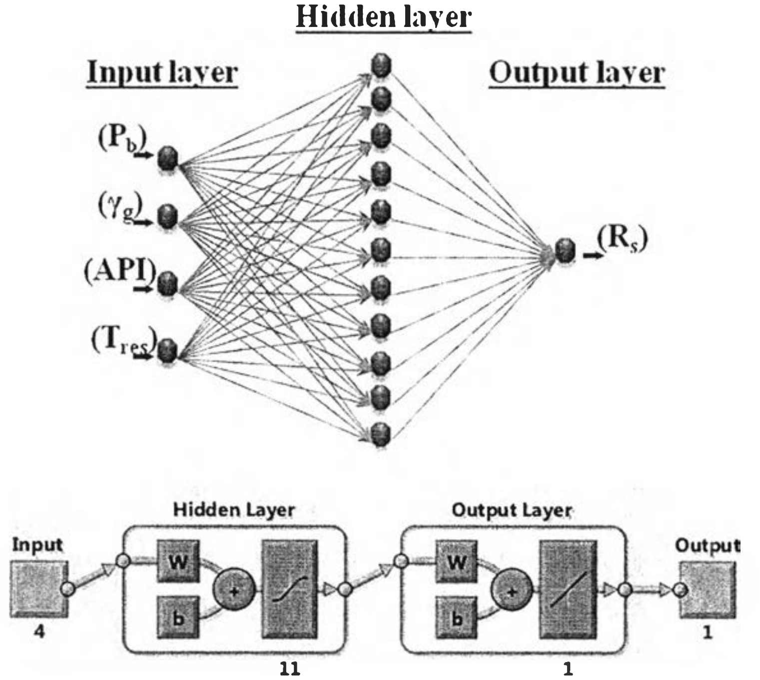

Figure 4.11 The architecture of the developed R_s ANN.

In addition, the regression plots and performance plots resulted from training the R_s ANN are depicted in Figure 4.11 and 4.12. The R values resulted from training the R_s ANN have the value above 0.96 for all the responses, while the MSE value validated from the R_s ANN is 8,709.68 at epoch 4. The connecting weights and biases of the R_s ANN are shown in Table 4.12.

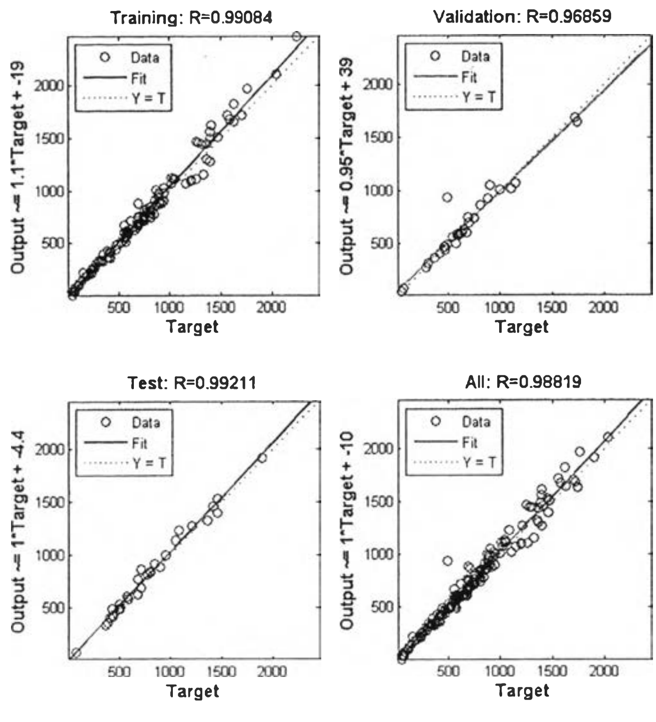

Figure 4.12 Regression plots of the R_s ANN outputs.

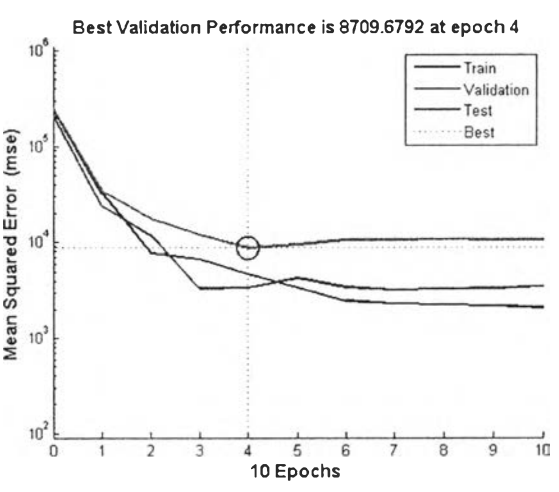

Figure 4.13 Performance plots of the developed R_s ANN.

Table 4.12 Connection weight and biases for the developed R_s neural network model

	W_{ji}											b_j
j/i	1	2	3	4	5	6	7	8	9	10	11	
First Layer												
1	0.99236	-0.73559	1.0989	1.9376								-1.7821
2	-1.5706	-1.3857	-0.94633	1.0411								1.8551
3	0.68951	1.7531	-1.4553	1.068								-1.5949
4	0.14542	1.4121	1.7477	-0.51542								-1.0191
5	-1.941	1.7102	0.38953	0.40357								0.38901
6	-0.63523	-1.3448	0.45067	2.0518								-0.11279
7	-1.1727	1.402	0.61674	-0.34716								-1.2616
8	-0.017742	1.3448	-0.47845	-2.2416								0.89616
9	-0.41216	0.39466	-0.63146	2.7098								-0.90662
10	-0.11717	-0.13075	2.4864	1.0164								-1.697
11	-1.3167	-2.0174	-0.84977	0.26514								-1.646
Second layer (output layer)												
1	0.1471	-0.15453	0.26219	1.9826	-0.047412	-0.051181	-0.76391	-0.066245	-0.085887	-0.85449	-0.47645	1.2469

4.3.4 Undersaturated Oil Viscosity Neural Network

In order to develop μ_o ANN, three input parameters, which are P_b, μ_{ob}, and P were used. 357 data points used for developing the ANN model (see section 4.1) were randomly divided into a set of 249 data points for training. A set of 49 data points was randomly selected for validation and another set of 49 data points was employed for testing the model. Finally, the 3-10-1 neural network architecture, shown in Figure 4.14, was selected for μ_o prediction.

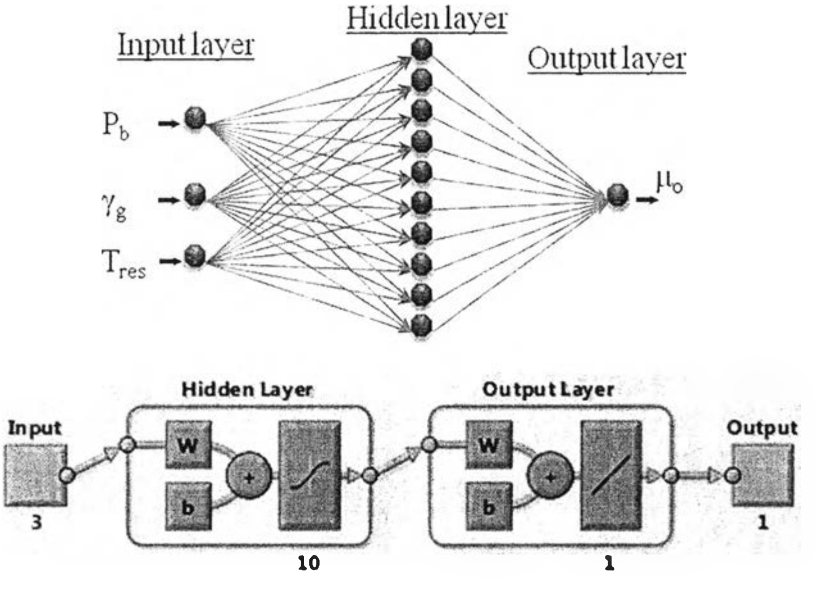

Figure 4.14 The architecture of the developed μ_o ANN.

Figure 4.15 illustrates the regression plots resulted from the outputs of the μ_o ANN which compare to the targets for training, validation, and testing. The graphical representation gave good-fitting results with the R value exceeding 0.99 for each response. The value of the MSE obtained from the validation performance of the developed μ_o ANN was 0.32241 at 26 epochs as shown in Figure 4.16. The connection weights and biases of the developed μ_o ANN are shown in Table 4.13.

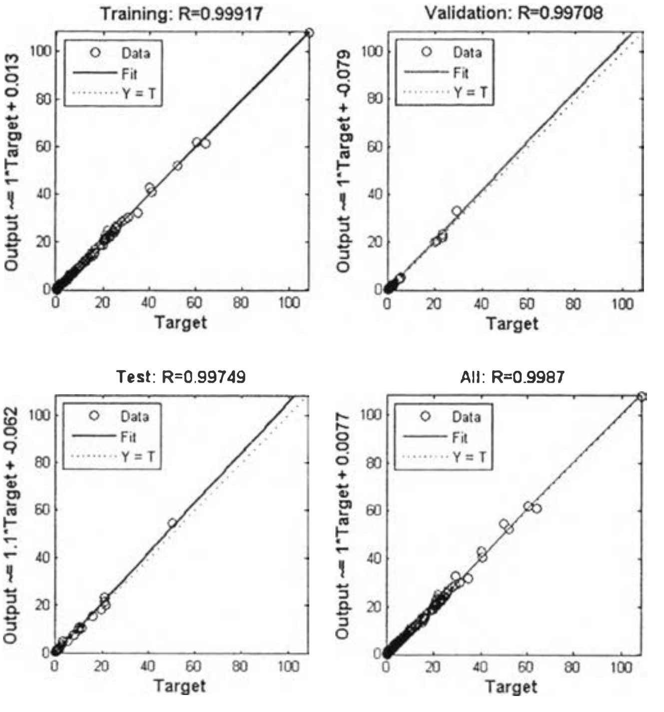

Figure 4.15 Regression plots of the μ_o ANN outputs.

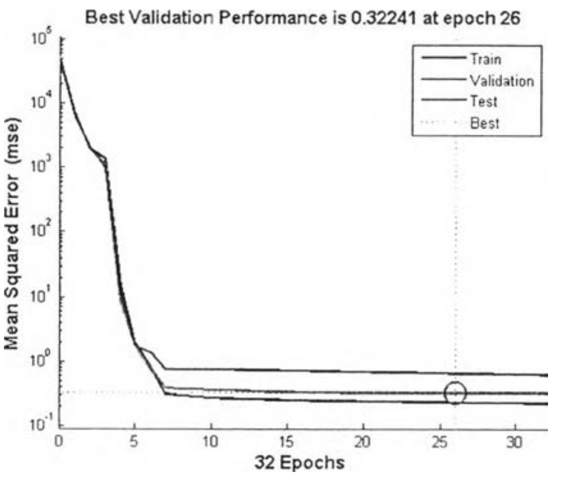

Figure 4.16 Performance plots of the developed μ_o ANN.

Table 4.13 Connection weights and biases for the developed μ_o neural network

	w_{ji}										b_j
j\i	1	2	3	4	5	6	7	8	9	10	
First layer											
1	50.6069	-4.1999	-8.5235								-21.2024
2	2.0448	-3.0648	-1.5013								-4.9377
3	12.4152	-10.2516	-6.3569								-4.2787
4	-0.91043	0.47302	1.8279								2.9978
5	-0.059353	0.050421	0.76089								0.0068025
6	2.0083	2.454	5.8789								11.9947
7	-0.52828	0.80617	-1.7411								-0.29849
8	-2.0051	2.791	4.4742								2.789
9	1.893	1.2556	6.8942								-6.5685
10	-2.3809	-0.34968	6.2977								8.0729
Second layer (output layer)											
1	0.00035858	5.4837	0.0025817	-0.20914	2.4453	1.5075	0.35764	-0.03868	-0.19741	0.013542	4.1268

4.4 Testing Results

The developed correlations and ANNs were tested against published correlations using the data sets for testing (the published correlation methods used for testing the developed models are summarized in Appendix A). The statistical results from the predictions of P_b, B_{ob}, R_s and μ_o using published correlations and the developed models are shown in Tables 4.11-4.14. As for the visual aid, the graphical plots for the testing results are also illustrated in Appendix B.

Table 4.14 Statistical results of P_b using testing data

Method	Er_{min}	Er_{max}	$\%AEr_{avg}$	$\%AEr_{max}$	R^2
Standing (1947)	-3139.93	1579.84	25.69	372.01	0.88929
Calhoun (1976)	-1882.76	1654.84	53.76	614.80	0.86888
Glaso (1980)	-4181.29	1228.53	27.62	247.00	0.87955
Vazquez and Beggs (1980)	-3869.91	1307.29	30.15	403.90	0.88920
Al-Marhoun (1988)	-4049.08	1894.29	23.20	131.62	0.83649
Petrosky Jr. and Farshad (1993)	-3035.26	1521.86	86.39	766.86	0.90579
Dokla and Osman (1991)	-1830.10	2243.37	29.80	206.23	0.79883
Kartoatmodjo and Schmidt (1991)	-4685.30	1179.75	34.54	487.43	0.87637
De Ghetto and Villa (1994)	-2617.00	1624.93	30.22	466.61	0.89587
Frashad et al. (1996)	-1620.52	1624.93	39.08	230.77	0.88458
Almehaideb (1997)	-3979.12	1724.54	34.32	427.18	0.82125
Velarde et al. (1997)	-1611.32	2117.66	21.12	110.45	0.87761
Hanafy et al. (1997)	-1882.76	1645.84	53.77	614.80	0.86888
Al-Shammasi (1999)	-1862.15	1642.29	18.09	105.65	0.89788
Valkó and Mccain Jr (2003)	-1566.93	1829.55	18.76	112.73	0.91467
Dindoruk and Christman (2004)	-1314.32	2703.91	25.94	152.31	0.80465
Nikpoor and Khanamiri (2011)	-2731.29	2077.11	20.72	115.40	0.85476
P_b correlation (Equation 4.1)	-1633.87	1693.76	22.36	185.92	0.91846
P_b ANN (this work)	-1519.51	1512.67	21.32	240.19	0.93176

Table 4.15 Statistical results of B_{ob} using testing data

Method	Er_{min}	Er_{max}	$\%AEr_{avg}$	$\%AEr_{max}$	R^2
Standing (1947)	-0.0214	1.5944	16.70	54.92	0.81238
Glaso (1980)	-0.1674	0.2695	2.84	11.61	0.97351
Al-Marhoun (1988)	-0.1014	0.2821	1.99	10.90	0.98026
Al-Marhoun (1992)	-0.0726	0.5773	3.56	20.00	0.97846
Omar and Todd (1993)	-0.0015	1.6115	17.87	55.51	0.84345
Petrosky Jr. and Farshad (1993)	-0.2337	0.1530	2.46	15.08	0.97582
Almehaideb (1997)	-0.2062	0.3171	4.23	17.73	0.93238
Hanafy et al. (1997)	-01.268	0.1512	7.97	43.93	0.93602
Al-Shammasi (1999)	-0.2136	0.4123	3.06	16.66	0.95197
Hemmati and Kharrat (2007)	-0.1789	0.1805	1.89	11.53	0.98179
Nikpoor and Khanamiri (2011)	-0.1421	0.4129	2.00	14.30	0.97513
B_{ob} correlation (Equation 4.2)	-0.1377	0.2189	1.67	8.21	0.98395
B_{ob} ANN (this work)	-0.1951	0.1876	2.13	9.67	0.98134

Table 4.16 Statistical results of R_s using testing data

Method	Er_{min}	Er_{max}	$\%AEr_{avg}$	$\%AEr_{max}$	R^2
Standing (1947)	-180.39	259.66	8.81	26.97	0.9848
Glaso (1980)	-220.49	589.67	14.64	50.02	0.9549
Al-Marhoun (1988)	-718.44	1335.15	19.62	200.83	0.7780
Petrosky Jr. and Farshad (1993)	-130.96	345.64	35.26	300.63	0.9835
Hemmati and Kharrat (2007)	-332.79	1424.27	11.85	100.14	0.8360
R_s correlation (Equation 4.3)	-206.15	254.68	6.88	20.50	0.9840
R_s ANN (this work)	-234.65	85.48	7.47	55.67	0.9909

Table 4.17 Statistical results of μ_o using testing data

Method	Er_{min}	Er_{max}	$\%AEr_{avg}$	$\%AEr_{max}$	R^2
Beal (1946)	-7.34	1.79	4.01	15.85	0.9979
Vazquez and Beggs (1980)	-3.08	11.91	12.77	39.74	0.9934
Khan (1987)	-0.27	10.05	3.37	15.97	0.9966
Kartoatmodjo and Schmidt (1991)	-7.36	1.64	4.54	21.35	0.9981
Petrosky and Farshad (1995)	-0.29	25.70	5.93	38.54	0.9664
Isehunwa et al. (2006)	-0.34	8.90	3.36	17.05	0.9974
Abedini et al. (2010)	3.28	-3.53	6.86	57.83	0.9969
μ_o correlation (Equation 4.4)	-0.80	3.56	3.79	24.88	0.9992
μ_o ANN (this work)	-27.51	1.62	13.97	81.67	0.9789

According to the P_b prediction results, presented in Table 4.11, the developed P_b ANN provided competitive performance compared to some of the published correlations. The developed P_b ANN had the best fit with the highest R^2 value (0.93176), where the R^2 value of the developed P_b correlation (Equation 4.1) had the second best result (0.91846). The developed P_b ANN gave 21.32 % AEr_{avg}, which is somewhat higher than several methods; however, the developed P_b ANN had the narrowest range of error (Er_{min} = -1519.51 psia, Er_{max} = 1512.67 psia, and range = 3032.18 psia). For the range of error of the developed P_b correlation, it is broader than the results obtained from the P_b ANN and Frashad's approach (Frashad et al., 1996).

In case of the B_{ob} prediction results, the developed B_{ob} correlation (Equation 4.2) outperformed other methods with the highest R^2 value of 0.98395, the lowest AEr_{avg} of 1.67 %, and the lowest AEr_{max} of 8.21 %. Moreover, the developed B_{ob} had the narrowest range of error (Er_{min} = -0.1951, Er_{max} = 0.2189, and range = 0.3827). The developed B_{ob} ANN had the second lowest result in terms of AEr_{max} (9.67 %). Also, other results from B_{ob} ANN including the R^2 value, the AEr_{avg}, and the range of error are noticeably competitive to the Hemmati-Kharrat's approach (Hemmati and Kharrat, 2007).

For the prediction results of R_s, as shown in Table 4.13, the developed R_s correlation (Equation 4.3) and the R_s ANN gave competitively lower values of AEr_{avg} (7.47 % AEr_{avg} for the developed correlation and 6.88 % AEr_{avg} for the R_s ANN) than other methods. Meanwhile, the developed R_s correlation exhibited the lowest AEr_{max} (20.5 %), but the R_s ANN gave higher AEr_{max} (55.67 %) than the developed R_s correlation (AEr_{max} = 20.5 %) and some existing approaches (i.e., Standing (1947) and Glaso (1980)). However, in terms of the R^2 value and the range of error, there are insignificant statistical outcomes compared to those from Standing's method and the R_s ANN.

For the prediction of μ_o, as presented in Table 4.14, the developed μ_o correlation (Equation 4.4) gave the highest R^2 value of 0.9992 and the narrowest range between Er_{min} (-0.8 cp) and Er_{max} (3.56 cp) with competitive performance compared to the published correlations by Beal (1946), Vazquez and Beggs (1980), Khan (1987), and Isehunwa et al. (2006). Although, the developed μ_o ANN had a good result in developing process (see section 4.3.2), it gave poor performance when using the testing data set with the highest range between Er_{min} and Er_{max}, highest AEr_{avg} and AEr_{max}, and lowest R^2. Thus, in order to check the applicability of an ANN, the ANN should be evaluated with different data set, and the appropriate size of the data set for developing process is also necessary.

Since the correlation approach does not need a computer, the correlation approach is therefore easier to be used. However, ANN approach can be quickly retrained using new data sets (i.e. regional data). ANN can also be practically applicable as long as the computer is accessible.