Chapter 4 Results and Discussion

The results and discussion are divided in two parts. First part discusses the effect of compression ratio and injection pressure on BTE, NOx, CO, HC and smoke emissions and also quantifies the NOx emission for the various combination of the parameters. The second phase of the chapter discuss the effect of the water injection on the exhaust emission elements like NOx, CO, HC and smoke.

4.1 Phase I Result and discussion

4.1.1 Observations and results

The observations and result table for various operating parameters are as below.

Table 4-1: Emission and Performance result; CR-15, IP-300 bar

CR-15, IP-300 bar		Emissions				Performance	
Fuel	Load (Kw)	NO (ppm)	HC (ppm)	CO (% vol.)	smoke	BTE (%)	SFC (kg/kWh)
Diesel	0.88	375	21	0.12	1.5	11.6	0.69
	1.75	689	20	0.09	1.4	20.1	0.4
	2.62	931	23	0.09	2.2	22.14	0.36
	3.5	994	39	0.21	5.8	22.54	0.35
B10	0.88	300	30	0.18	5.7	12.72	0.64
	1.75	550	34	0.15	4.9	20.14	0.41
	2.62	751	33	0.147	6.2	19.83	0.41
	3.5	918	43	0.27	8.2	24.64	0.33
B20	0.88	313	35	0.19	4	13.49	0.62
	1.75	630	38	0.16	4.6	19.23	0.44
	2.62	844	46	0.22	8.5	20.96	0.4
	3.5	763	48	0.3	18.8	20.53	0.41
B30	0.88	198	39	0.23	1.1	12.5	0.68
	1.75	524	35	0.17	3.1	18.23	0.47
	2.62	812	41	0.21	5.7	21.44	0.4
	3.5	731	40	0.22	17.9	24.02	0.35

Table 4-2:Emission and Performance result; CR-15, IP-400 bar

CR-15, IP-400 bar		Emissions				Performance	
Fuel	Load (Kw)	NO (ppm)	HC (ppm)	CO (% vol.)	smoke	BTE (%)	SFC (kg/kWh)
Diesel	0.88	305	30	0.17	1.4	13.06	0.61
	1.75	835	29	0.11	2.3	19.18	0.41
	2.62	1212	29	0.11	1.8	19.37	0.41
	3.5	1125	34	0.18	6.1	22.75	0.35
B10	0.88	220	36	0.24	5.3	13.05	0.63
	1.75	639	32	0.16	4.3	17.66	0.46
	2.62	988	40	0.15	5.7	23.65	0.35
	3.5	1080	44	0.24	14	23.21	0.35
B20	0.88	185	40	0.27	2.6	12.87	0.65
	1.75	653	42	0.17	3.9	18.26	0.46
	2.62	1056	46	0.17	6.1	19.75	0.42
	3.5	1189	57	0.32	14.6	23.88	0.35
B30	0.88	136	36	0.28	1.4	12.88	0.66
	1.75	596	42	0.18	3.5	19.74	0.43
	2.62	1106	35	0.15	5.3	22.07	0.39
	3.5	1311	43	0.25	8.4	23.79	0.36

Table 4-3:Emission and Performance result; CR-15, IP-500 bar

CR-15, IP-500 bar		Emissions				Performance	
Fuel	Load (Kw)	NO (ppm)	HC (ppm)	CO (% vol.)	smoke	BTE (%)	SFC (kg/kWh)
Diesel	0.88	249	31	0.21	1	12	0.66
	1.75	944	38	0.12	2	16.64	0.48
	2.62	1204	41	0.14	2.5	21.39	0.37
	3.5	1189	40	0.17	6	23.81	0.33
B10	0.88	184	38	0.29	2.6	13.29	0.61
	1.75	756	43	0.17	3.4	18.06	0.45
	2.62	1247	37	0.14	4.6	21.4	0.38
	3.5	1118	37	0.21	14	23.92	0.34
B20	0.88	171	43	0.32	2.6	12.5	0.67
	1.75	750	46	0.2	3.5	18.6	0.45
	2.62	1213	49	0.15	5.2	19.8	0.42
	3.5	1155	55	0.3	15.4	21.19	0.4
B30	0.88	94	38	0.32	0.8	13.23	0.64
	1.75	563	41	0.19	2.8	17.46	0.49
	2.62	1179	44	0.15	4.7	22.29	0.38
	3.5	1289	44	0.24	8.8	22.92	0.37

Table 4-4:Emission and Performance result; CR-15, IP-600 bar

CR-15, IP-600 bar		Emissions				Performance	
Fuel	Load (Kw)	NO (ppm)	HC (ppm)	CO (% vol.)	smoke	BTE (%)	SFC (kg/kWh)
Diesel	0.88	195	29	0.22	0.8	12.61	0.63
	1.75	850	38	0.11	1.8	16.67	0.48
	2.62	1149	45	0.17	3.2	19.94	0.4
	3.5	1168	46	0.17	5.4	22.62	0.35
B10	0.88	133	37	0.35	1.5	13.22	0.62
	1.75	727	40	0.18	2.7	19.27	0.42
	2.62	1161	42	0.15	3.2	20.41	0.4
	3.5	1105	45	0.23	6.9	23.1	0.35
B20	0.88	46	44	0.39	2.2	12.81	0.65
	1.75	719	47	0.19	6.2	17.58	0.48
	2.62	1246	45	0.18	5.3	20.22	0.41
	3.5	1139	47	0.28	9.8	22.12	0.38
B30	0.88	49	36	0.36	0.7	12.48	0.68
	1.75	550	38	0.2	3.4	20.16	0.42
	2.62	1151	38	0.15	6	22.1	0.39
	3.5	1311	42	0.22	8.5	24	0.35

Table 4-5:Emission and Performance result; CR-16, IP-300 bar

CR-16, IP-300 bar		Emissions				Performance	
Fuel	Load (Kw)	NO (ppm)	HC (ppm)	CO (% vol.)	smoke	BTE (%)	SFC (kg/kWh)
Diesel	0.88	420	29	0.1	4.1	13.86	0.57
	1.75	686	35	0.1	4.2	19.11	0.42
	2.62	826	40	0.14	6	21.76	0.37
	3.5	889	55	0.21	13.9	22.42	0.36
B10	0.88	361	21	0.14	5	18.17	0.45
	1.75	626	24	0.12	3.9	23.57	0.35
	2.62	838	32	0.18	6.6	21.93	0.37
	3.5	880	44	0.3	17.5	23.36	0.35
B20	0.88	342	27	0.17	3.8	13.14	0.64
	1.75	655	33	0.14	4.6	19.08	0.44
	2.62	809	33	0.19	7.2	21.2	0.4
	3.5	693	36	0.22	20.6	20.94	0.4
B30	0.88	305	26	0.16	1.4	12.46	0.68
	1.75	652	31	0.13	3.3	18.36	0.46
	2.62	913	35	0.14	5.6	21.75	0.39
	3.5	1011	43	0.21	14.3	22.77	0.37

Table 4-6:Emission and Performance result; CR-16, IP-400 bar

CR-16, IP-400 bar		Emissions				Performance	
Fuel	Load (Kw)	NO (ppm)	HC (ppm)	CO (% vol.)	smoke	BTE (%)	SFC (kg/kWh)
Diesel	0.88	346	30	0.15	4.5	11.55	0.69
	1.75	756	41	0.13	5.7	19.21	0.41
	2.62	1086	44	0.19	5.2	20.04	0.4
	3.5	1022	48	0.21	8.7	22.53	0.35
B10	0.88	308	24	0.2	4.6	18.18	0.45
	1.75	775	27	0.14	3.6	25.61	0.32
	2.62	1064	33	0.18	5.8	28.48	0.29
	3.5	976	42	0.27	16.4	30.48	0.27
B20	0.88	294	30	0.21	3.3	12.33	0.68
	1.75	781	33	0.14	4.1	17.83	0.47
	2.62	990	38	0.21	6.7	21.42	0.39
	3.5	1028	40	0.32	16.7	22.89	0.37
B30	0.88	198	24	0.2	1.1	12.11	0.7
	1.75	707	31	0.14	3.4	18.59	0.46
	2.62	1163	36	0.14	4.6	20.77	0.41
	3.5	1331	39	0.22	12.7	24.07	0.35

Table 4-7:Emission and Performance result; CR-16, IP-500 bar

CR-16, IP-500 bar		Emissions				Performance	
Fuel	Load (Kw)	NO (ppm)	HC (ppm)	CO (% vol.)	smoke	BTE (%)	SFC (kg/kWh)
Diesel	0.88	383	42	0.19	3.1	11.48	0.69
	1.75	846	51	0.15	3.7	15.67	0.51
	2.62	1028	40	0.2	4.3	19.14	0.42
	3.5	983	47	0.22	8.9	22.7	0.35
B10	0.88	298	30	0.23	5	16.02	0.51
	1.75	939	35	0.13	4.8	23.5	0.35
	2.62	1103	28	0.15	3.8	26.45	0.31
	3.5	1015	42	0.3	17	29.07	0.28
B20	0.88	255	39	0.26	3.5	11.96	0.7
	1.75	890	40	0.15	4.1	17.33	0.48
	2.62	1220	35	0.18	6.6	20.07	0.42
	3.5	1155	45	0.31	16.3	22.07	0.38
B30	0.88	133	18	0.26	1.4	12.19	0.7
	1.75	667	25	0.16	4.2	18.3	0.47
	2.62	1289	27	0.16	3.9	21.23	0.4
	3.5	1316	31	0.22	9.2	22.2	0.38

Table 4-8:Emission and Performance result; CR-16, IP-600 bar

CR-16, IP-600 bar		Emissions				Performance	
Fuel	Load (Kw)	NO (ppm)	HC (ppm)	CO (% vol.)	smoke	BTE (%)	SFC (kg/kWh)
Diesel	0.88	252	29	0.2	0.3	10.99	0.72
	1.75	891	44	0.15	2.2	18.93	0.42
	2.62	1119	50	0.19	2.4	20.02	0.4
	3.5	1039	55	0.22	6.5	20.84	0.38
B10	0.88	233	25	0.25	1	16.08	0.51
	1.75	875	31	0.14	3.1	23.92	0.34
	2.62	1150	34	0.15	4	30.55	0.27
	3.5	1023	41	0.27	14.3	30.68	0.27
B20	0.88	189	40	0.31	2.3	12.41	0.68
	1.75	868	46	0.18	5.5	17.3	0.48
	2.62	1174	46	0.2	6.5	21.82	0.38
	3.5	1129	52	0.31	15.1	21.87	0.38
B30	0.88	83	23	0.29	0.6	12.09	0.7
	1.75	689	24	0.14	2	17.45	0.49
	2.62	1191	30	0.18	5.4	20.46	0.42
	3.5	1334	26	0.21	7.2	23.17	0.37

Table 4-9:Emission and Performance result; CR-17, IP-300 bar

CR-17, IP-300 bar		Emissions				Performance	
Fuel	Load (Kw)	NO (ppm)	HC (ppm)	CO (% vol.)	smoke	BTE (%)	SFC (kg/kWh)
Diesel	0.88	536	41	0.1	2.9	12.31	0.65
	1.75	702	43	0.1	3.1	17.38	0.46
	2.62	805	46	0.13	5	20.04	0.4
	3.5	969	57	0.16	7	21.71	0.37
B10	0.88	509	22	0.1	4.1	17.74	0.46
	1.75	764	26	0.1	3.5	25.65	0.32
	2.62	918	25	0.14	5	27.76	0.29
	3.5	1024	31	0.21	15.2	30.21	0.27
B20	0.88	489	30	0.14	1.9	10.9	0.77
	1.75	760	38	0.15	3.2	19.1	0.44
	2.62	907	36	0.21	4.4	20.34	0.41
	3.5	960	45	0.25	9.7	23.13	0.36
B30	0.88	441	18	0.12	1.9	13.55	0.63
	1.75	733	20	0.11	3	19.67	0.43
	2.62	895	24	0.15	6.4	22.8	0.37
	3.5	806	23	0.17	20.1	24.65	0.35

Table 4-10:Emission and Performance result; CR-17, IP-400 bar

CR-17, IP-400 bar		Emissions				Performance	
Fuel	Load (Kw)	NO (ppm)	HC (ppm)	CO (% vol.)	smoke	BTE (%)	SFC (kg/kWh)
Diesel	0.88	476	34	0.11	1.6	12.31	0.65
	1.75	939	46	0.11	2.5	17.38	0.46
	2.62	1201	50	0.14	2.7	20.04	0.4
	3.5	1144	56	0.17	8.8	21.71	0.37
B10	0.88	565	27	0.13	4.8	18.19	0.45
	1.75	944	30	0.11	3.8	23.92	0.34
	2.62	1121	34	0.18	4.4	28.44	0.29
	3.5	1140	37	0.22	13.8	32.37	0.25
B20	0.88	419	29	0.15	1.8	12.41	0.68
	1.75	891	39	0.15	3.3	17.42	0.48
	2.62	1115	46	0.21	5	19.69	0.43
	3.5	1204	53	0.28	8.1	22.1	0.38
B30	0.88	353	22	0.14	3.1	12.48	0.68
	1.75	892	27	0.11	3	18.56	0.46
	2.62	1200	30	0.14	6.2	20.59	0.41
	3.5	1327	35	0.26	8	22.14	0.38

Table 4-11:Emission and Performance result; CR-17, IP-500 bar

CR-17, IP-500 bar		Emissions				Performance	
Fuel	Load (Kw)	NO (ppm)	HC (ppm)	CO (% vol.)	smoke	BTE (%)	SFC (kg/kWh)
Diesel	0.88	490	28	0.11	3.3	11.61	0.69
	1.75	1096	35	0.11	3.9	16.67	0.48
	2.62	1243	42	0.16	4	22.26	0.36
	3.5	1074	45	0.17	7.8	21.56	0.37
B10	0.88	538	32	0.15	3.1	16.15	0.51
	1.75	1140	31	0.13	3	22.09	0.37
	2.62	1275	33	0.19	4	28.49	0.29
	3.5	1143	38	0.24	15.9	30.71	0.27
B20	0.88	379	32	0.2	2.4	11.78	0.71
	1.75	1097	42	0.17	3.7	16.57	0.51
	2.62	1316	47	0.24	5.3	21.15	0.4
	3.5	1272	50	0.27	8.7	22.08	0.38
B30	0.88	330	28	0.18	1.9	12.23	0.7
	1.75	1107	31	0.12	4.3	17.71	0.48
	2.62	1417	37	0.17	5	21.11	0.4
	3.5	1327	35	0.24	14	22.18	0.38

Table 4-12:Emission and Performance result; CR-17, IP-600 bar

CR-17, IP-600 bar		Emissions				Performance	
Fuel	Load (Kw)	NO (ppm)	HC (ppm)	CO (% vol.)	smoke	BTE (%)	SFC (kg/kWh)
Diesel	0.88	470	42	0.14	2	13.02	0.61
	1.75	1128	40	0.1	2.2	17.61	0.45
	2.62	1281	42	0.15	2.6	22.16	0.36
	3.5	1134	45	0.17	6.8	20.77	0.38
B10	0.88	566	26	0.16	1.1	16.1	0.51
	1.75	1217	35	0.13	1.4	22.38	0.37
	2.62	1325	40	0.2	2.5	28.56	0.29
	3.5	1130	42	0.26	9	32.47	0.25
B20	0.88	394	31	0.19	1.1	12.52	0.67
	1.75	1206	35	0.13	2.3	15.68	0.53
	2.62	1400	42	0.21	4.1	20.19	0.42
	3.5	1289	50	0.28	6.4	21.24	0.39
B30	0.88	298	34	0.24	1.8	12.45	0.68
	1.75	1067	34	0.16	3.8	16.41	0.52
	2.62	1476	41	0.21	6.2	19.12	0.45
	3.5	1324	39	0.26	8.5	21.52	0.4

Table 4-13:Emission and Performance result; CR-18, IP-300 bar

CR-18, IP-300 bar		Emissions				Performance	
Fuel	Load (Kw)	NO (ppm)	HC (ppm)	CO (% vol.)	smoke	BTE (%)	SFC (kg/kWh)
Diesel	0.88	791	55	0.08	3.1	13.02	0.61
	1.75	1033	60	0.09	1.5	17.34	0.46
	2.62	1036	58	0.12	5.3	20.74	0.38
	3.5	1089	59	0.12	7	21.55	0.37
B10	0.88	756	26	0.08	2.5	13.25	0.62
	1.75	1017	30	0.1	2.8	18.85	0.43
	2.62	1110	34	0.13	5	22.15	0.37
	3.5	1111	43	0.14	8.6	34.11	0.24
B20	0.88	727	28	0.09	1.6	12.8	0.65
	1.75	980	33	0.11	2.6	17.82	0.47
	2.62	1113	28	0.15	4.6	21.51	0.39
	3.5	1102	31	0.18	8.8	22.52	0.37
B30	0.88	710	27	0.12	0.6	12.05	0.71
	1.75	948	34	0.15	4.1	18.14	0.47
	2.62	1017	34	0.17	6.8	21.3	0.4
	3.5	896	29	0.19	17.4	24.64	0.35

Table 4-14: Emission and Performance result; CR-18, IP-400 bar

CR-18, IP-400 bar		Emissions				Performance	
Fuel	Load (Kw)	NO (ppm)	HC (ppm)	CO (% vol.)	smoke	BTE (%)	SFC (kg/kWh)
Diesel	0.88	830	111	0.07	2.2	11.68	0.68
	1.75	1247	99	0.09	3.5	17.7	0.45
	2.62	1417	90	0.12	4.1	20.77	0.38
	3.5	1282	83	0.14	5.1	21.69	0.37
B10	0.88	881	29	0.09	2.5	12.02	0.68
	1.75	1271	36	0.11	2.2	15.89	0.51
	2.62	1474	42	0.12	2.5	21.14	0.39
	3.5	1285	33	0.18	8.1	21.23	0.38
B20	0.88	782	31	0.12	3.5	12.43	0.67
	1.75	1094	37	0.16	3.9	17.49	0.48
	2.62	1242	42	0.21	5.9	20.63	0.41
	3.5	1340	45	0.24	7.4	22.69	0.37
B30	0.88	732	27	0.13	0	11.24	0.76
	1.75	1124	37	0.17	2.2	17.29	0.49
	2.62	1259	39	0.23	6.3	19.62	0.43
	3.5	1202	42	0.32	13.4	21.95	0.39

Table 4-15:Emission and Performance result; CR-18, IP-500 bar

CR-18, IP-500 bar		Emissions				Performance	
Fuel	Load (Kw)	NO (ppm)	HC (ppm)	CO (% vol.)	smoke	BTE (%)	SFC (kg/kWh)
Diesel	0.88	865	261	0.11	3.8	11.91	0.67
	1.75	1302	229	0.15	3.9	16.36	0.49
	2.62	1410	147	0.19	5.8	19.87	0.4
	3.5	1320	142	0.16	15.8	21.66	0.37
B10	0.88	929	30	0.11	3.3	10.8	0.76
	1.75	1512	41	0.15	3.7	16.87	0.48
	2.62	1727	46	0.16	5.5	19.41	0.42
	3.5	1370	45	0.16	9.8	19.74	0.41
B20	0.88	901	34	0.14	3.5	10.63	0.79
	1.75	1419	39	0.19	5	15.5	0.54
	2.62	1585	42	0.28	4.7	20	0.42
	3.5	1457	42	0.29	6.6	19.92	0.42
B30	0.88	761	29	0.14	3.7	11.07	0.77
	1.75	1351	30	0.16	6.7	16.75	0.51
	2.62	1651	36	0.26	6.8	18.79	0.45
	3.5	1398	37	0.33	13.6	22.43	0.38

Table 4-16:Emission and Performance result; CR-18, IP-600 bar

CR-18, IP-600 bar		Emissions				Performance	
Fuel	Load (Kw)	NO (ppm)	HC (ppm)	CO (% vol.)	smoke	BTE (%)	SFC (kg/kWh)
Diesel	0.88	770	235	0.1	0.1	11.33	0.7
	1.75	1301	239	0.15	2.7	15.47	0.51
	2.62	1421	274	0.19	4.6	18.94	0.42
	3.5	1237	360	0.19	16.7	21.46	0.37
B10	0.88	976	37	0.11	1.5	10.76	0.76
	1.75	1487	44	0.15	1.8	16.13	0.51
	2.62	1674	43	0.24	1.5	19.5	0.42
	3.5	1659	46	0.19	4	22.29	0.37
B20	0.88	1053	26	0.12	1	9.3	0.9
	1.75	1775	41	0.21	2.7	14.7	0.57
	2.62	1953	43	0.28	4.3	18.2	0.46
	3.5	1643	44	0.29	6.8	21.28	0.39
B30	0.88	813	28	0.15	2.3	10.09	0.84
	1.75	1629	40	0.18	2.7	15.83	0.54
	2.62	1802	40	0.27	4	17.41	0.49
	3.5	1468	41	0.4	8.6	21.83	0.39

4.1.2 Brake Thermal Efficiency

We examined the engine's brake thermal efficiency using four different fuels: diesel (B0), B10, B20, and B30. We tested these fuels at different compression ratios (15:1, 16:1, 17:1, and 18:1) and injection pressures (300, 400, 500, and 600 bar), while subjecting the engine to varying load conditions (25%, 50%, 75%, and 100%). This section presents an analysis of the outcomes obtained from these parameters.

Brake thermal efficiency is an essential performance indicator used for predicting the efficiency of converting fuel energy into useful work. The calculation involves dividing the engine's brake power by the energy input to the system. Figure 4-1 displays the changes in brake thermal efficiency for various fuel blends (Diesel, B10, B20, and B30) and injection pressures (300, 400, 500, and 600 bar) at a compression ratio of 15 bar and a constant speed of 1500 rpm. These measurements were taken under different load conditions (25%, 50%, 75%, and 100%). The brake thermal efficiency of the B30 blend exhibits an increase when the injection pressure is raised to 600 bar, regardless of the load circumstances (50%, 75%, and 100%) and fuel mixes.

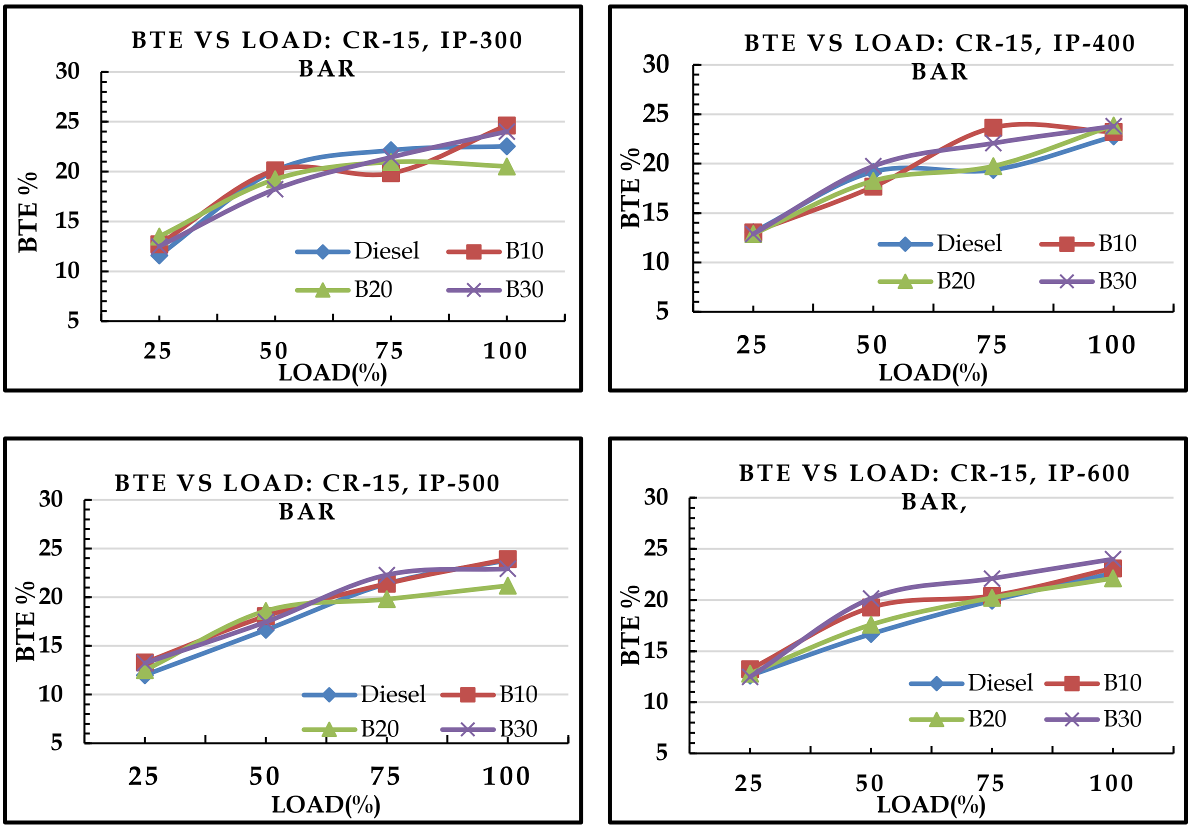


Figure 4-1:Variation in BTE with load at CR 15 for different fuel blends and IP

The BTE values for injection pressure of 600 bar at full load for diesel, B10, B20, and B30 are 22.62%, 23.10%, 22.12%, and 24%, respectively. Among all injection pressures at CR 15 under full load, the B10 blend exhibited a superior Brake Thermal Efficiency of 24.64% compared to all other evaluated fuels. This is due to the lubricating properties offered by biodiesel. Biodiesel molecules possess supplementary oxygen that actively engages in the process of combustion, resulting in enhanced combustion. B10 blends have superior Brake Thermal Efficiency compared to B20 and B30 blends because to the higher density and viscosity, as well as the lower calorific value, of B20 and B30 blends. This indicates that there is poor mixing between the air and fuel, resulting in the formation of larger droplets when the fuel is atomized. Figure 4-2 illustrates the changes in brake thermal efficiency for various fuel blends (Diesel, B10, B20, and B30) and injection pressures (300, 400, 500, and 600 bar) at a compression ratio of 16 and a constant speed of 1500 rpm.

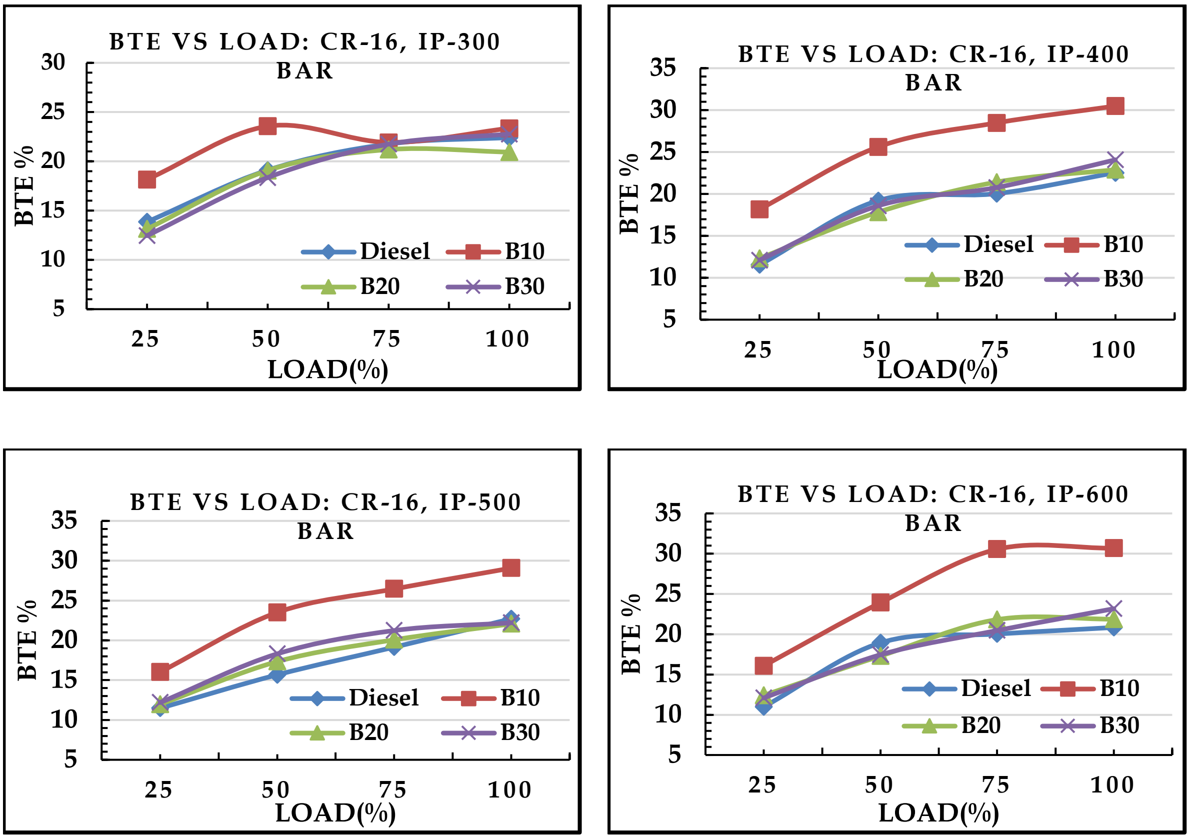


Figure 4-2:Variation in BTE with load at CR 16 for different fuel blends and IP

These variations are seen at different load conditions (25%, 50%, 75%, and 100%). The trials demonstrated that the B10 blend surpasses all other gasoline blends in performance when the compression ratio is set at 16, regardless of injection pressure and load conditions. The maximum value of Brake Thermal Efficiency is 30.68%, observed at an intake pressure of 600 bar at full load conditions. This value is 47.21% greater than that of diesel fuel under the same conditions. The presence of oxygen molecules in biodiesel enhances combustion efficiency, leading to enhanced combustion. As the injection pressure increases, the brake thermal efficiency likewise increases. This is because higher injection pressure causes the fuel droplets to break into smaller particles more quickly than at lower injection pressure. This leads to improved atomization and more efficient combustion. Increased fuel mixes lead to a reduction in Brake Thermal Efficiency due to a fall in calorific value and an increase in fuel blend usage. Figure 4-3 illustrates the changes in brake thermal efficiency for various fuel blends (Diesel, B10, B20, and B30) and injection pressures (300, 400, 500, and 600 bar) at a compression ratio of 17 and a constant speed of 1500 rpm, while the load circumstances vary between 25%, 50%, 75%, and 100%.

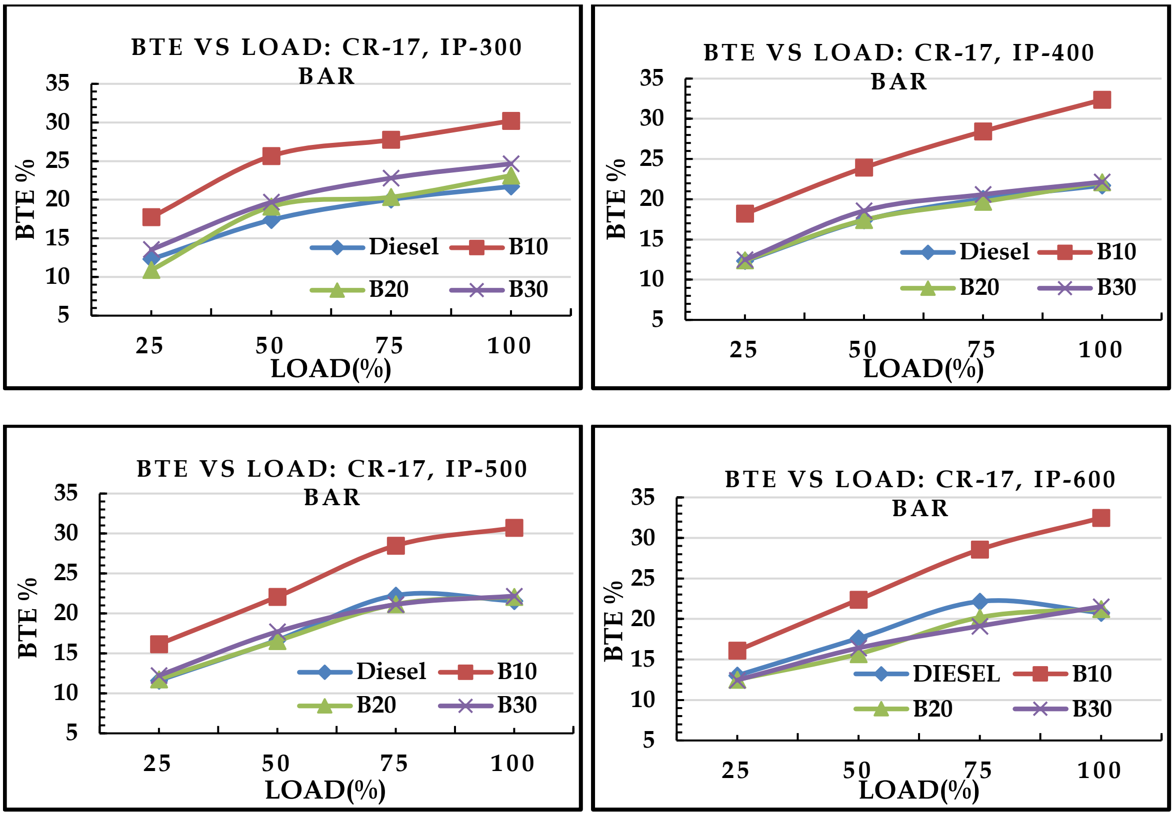


Figure 4-3:Variation in BTE with load at CR 17 for different fuel blends and IP

The decreased BTE (Brake Thermal Efficiency) of higher blends is attributed to their low calorific value and an inadequate air-fuel combination. As the load increases from 25% to 100%, the brake thermal efficiency also increases. This is because higher loads generate more braking power, resulting in fewer heat losses. The brake thermal efficiency rises in correlation with the increase in injection pressure due to the fragmentation of fuel droplets into smaller particles, which enables faster injection into the cylinder compared to fuels with lower IP. Under full load conditions, the Brake Thermal Efficiency values for IP 300, 400, 500, and 600 bar are 30.21%, 32.37%, 30.71%, and 32.47% respectively, at a Compression Ratio of 17.

Figure 4-4 illustrates the changes in brake thermal efficiency for several fuel blends (Diesel, B10, B20, and B30) and injection pressures (300, 400, 500, and 600 bar) at a compression ratio of 18 and a constant speed of 1500 rpm. These measurements were taken under different load circumstances (25%, 50%, 75%, and 100%). The investigations revealed that at 300 bar IP and CR 18 under full load, the brake thermal efficiency of B10 is 12.56% greater than that of diesel fuel. This can be attributed to the higher oxygen content in B10, which likely led to enhanced combustion compared to diesel.

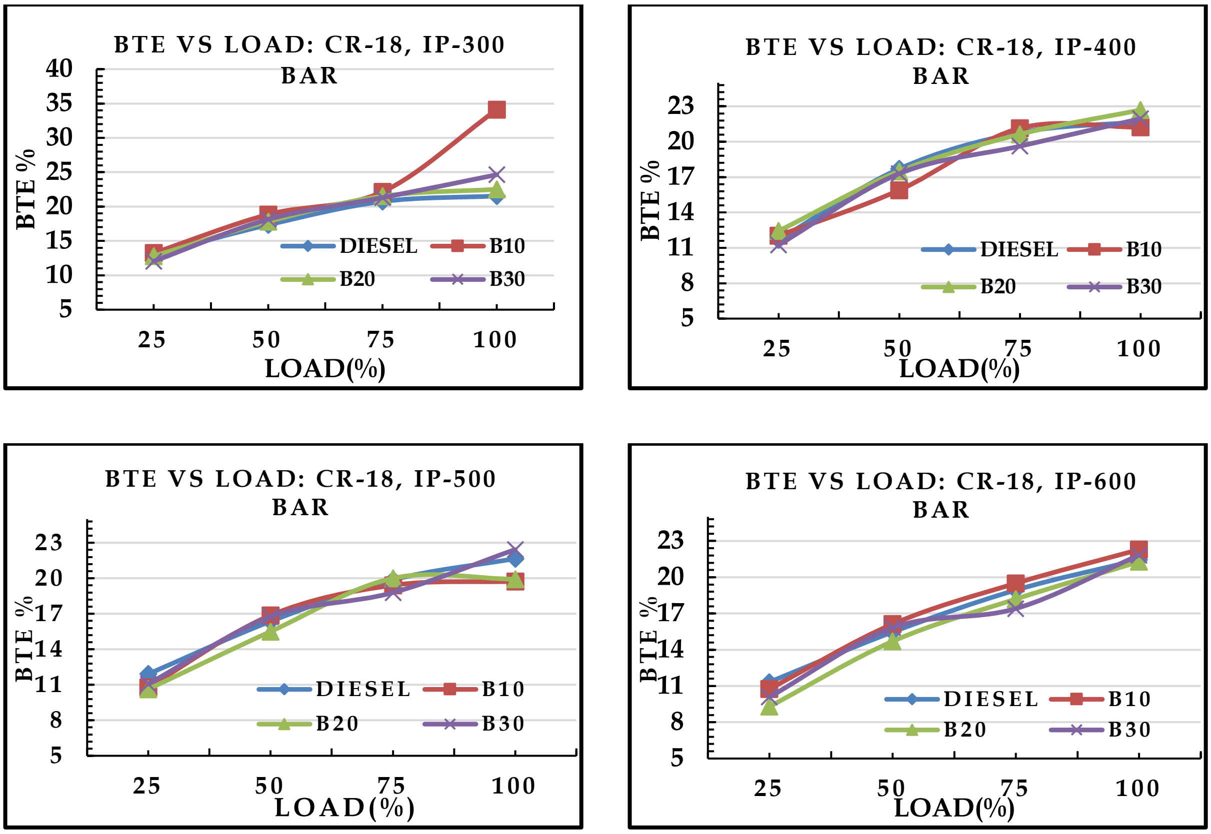


Figure 4-4:Variation in BTE with load at CR 18 for different fuel blends and IP

As the load percentage increases, the brake thermal efficiency also increases since the increased load generates more braking power. The B10 fuel blend exhibits improved brake thermal efficiency by 58% as compared to diesel fuel at full load condition for the compression ratio of 18 and an injection pressure of 300, owing to increased pressure and temperature within the combustion chamber.

Summary of Brake Thermal Efficiency

The BTE rises proportionally with a rise in load. The improvement in brake power is a result of lower heat losses at greater loads. The decrease in Brake Thermal Efficiency for a greater blend % may be attributed to the lower heating value and increased fuel consumption of the MLME blend.

The BTE (brake thermal efficiency) of the B10 blend is higher than that of diesel fuel due to the presence of oxygen molecules in biodiesel, which enhance combustion efficiency. Increasing the compression ratio in a low-capacity diesel engine leads to elevated temperature and pressure within the cylinder. This causes a decrease in ignition delay and an increase in heat release rate and brake power, resulting in a higher brake thermal efficiency. As the injection pressure increases, the brake thermal efficiency also increases because the fuel droplets are broken down into smaller particles at high injection pressure. This enables faster injection into the cylinder compared to low injection pressure. This mechanism results in enhanced atomization and combustion. Out of all the fuel blends that were tested, the B10 blend had the greatest Brake Thermal Efficiency value of 34.11%. This was achieved while maintaining a compression ratio of 18 and an Injection Pressure of 300 bar under full load conditions.

4.1.3 Carbon monoxide Emission (CO)

Figure 4-5 displays variations in carbon monoxide discharge for the fuel blends (B0, B10, B20, and B30) that were tested at different injection pressures (300, 400, 500, and 600 bar) and compression ratio 15, while the load circumstances varied from 25% to 100%. It has been shown that when the load grows, the concentration of carbon monoxide in the exhaust gas initially falls till reaching 75% load, and then increases again at full load. At low loads, the temperature of the gas within the engine cylinder stays low, leading to incomplete combustion in the gas phase and significantly elevated emissions of carbon monoxide. As the load on the engine grows, the emission of carbon monoxide decreases because the increasing temperature of the gas inside the cylinder increases the rate at which CO is oxidized.

The carbon monoxide emission reduces proportionally as the load increases, reaching a reduction of up to 75% for all tested fuel blends at an injection pressure of 15 in the common rail system. CO emissions grow beyond 75% load, reaching full load condition, due to the proportional increase in fuel consumption. The B10 blend exhibits a 7.15% reduction in carbon monoxide emissions compared to the B20 and B30 blends when tested at compression ratio 15 and injection pressure of 500 bar, at a load condition of 75%. The increased CO emissions observed in case of B20 and B30 blends compared to B10 and diesel fuel might be attributed to factors such as the kinematic viscosity, lower heating value, poor atomization, and poor volatility of these blends. These characteristics result in incomplete combustion. Figure 4-6 displays the levels of carbon monoxide emissions for the fuel blends (B0, B10, B20, and B30) that were evaluated at varied injection pressures (300, 400, 500, and 600 bar) and a compression ratio of 16.

The emissions were measured under different load circumstances ranging from 25% to 100%. It has been shown that carbon monoxide emissions drop as the load increases from 25% to 50%.

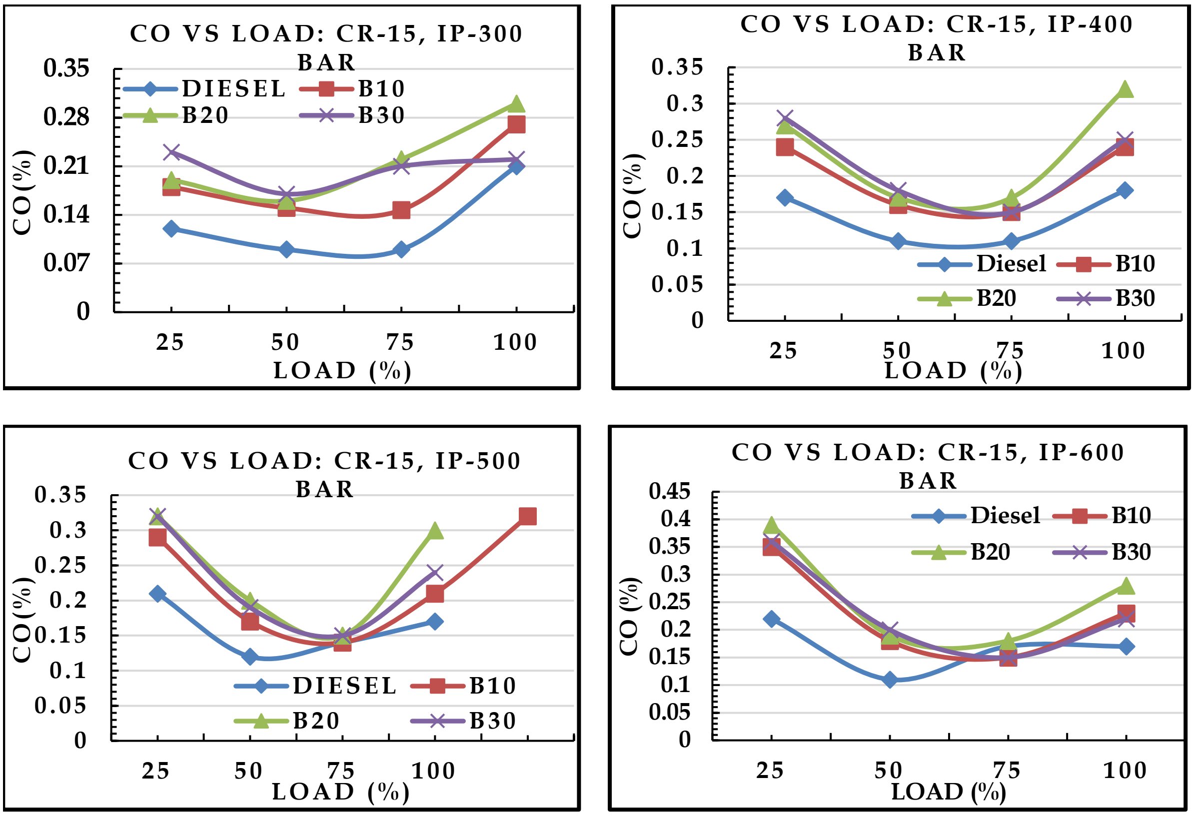


Figure 4-5: Variation in CO emission with load at CR 15

However, with a load of 50%, the CO emissions begin to rise. At low loads, the temperature of the gas within the engine cylinder stays low, leading to incomplete combustion in the gas phase and significantly elevated emissions of carbon monoxide. Under full load conditions, a significant quantity of fuel is injected, leading to an uneven distribution and incorrect mixing, which in turn results in a high concentration of carbon monoxide.

The B10 blend, evaluated at CR 16 and IP 500 bar, exhibited the lowest CO emission value of 0.13% among all the fuel blends tested. The presence of oxygen molecules in the biodiesel facilitated complete combustion, resulting in a decrease in CO emissions in the cylinder. Figure 4-7 illustrates the concentrations of carbon monoxide emissions for the fuel blends (B0, B10, B20, and B30) that were tested at varied injection pressures (300, 400, 500, and 600 bar) and compression ratio 17, while subject to varying load circumstances ranging from 25% to 100%. It has been noted that when the load increases from 25% to 50%, the generation of carbon monoxide reduces for all the fuels evaluated at a compression ratio of 17 among all the injection pressures.

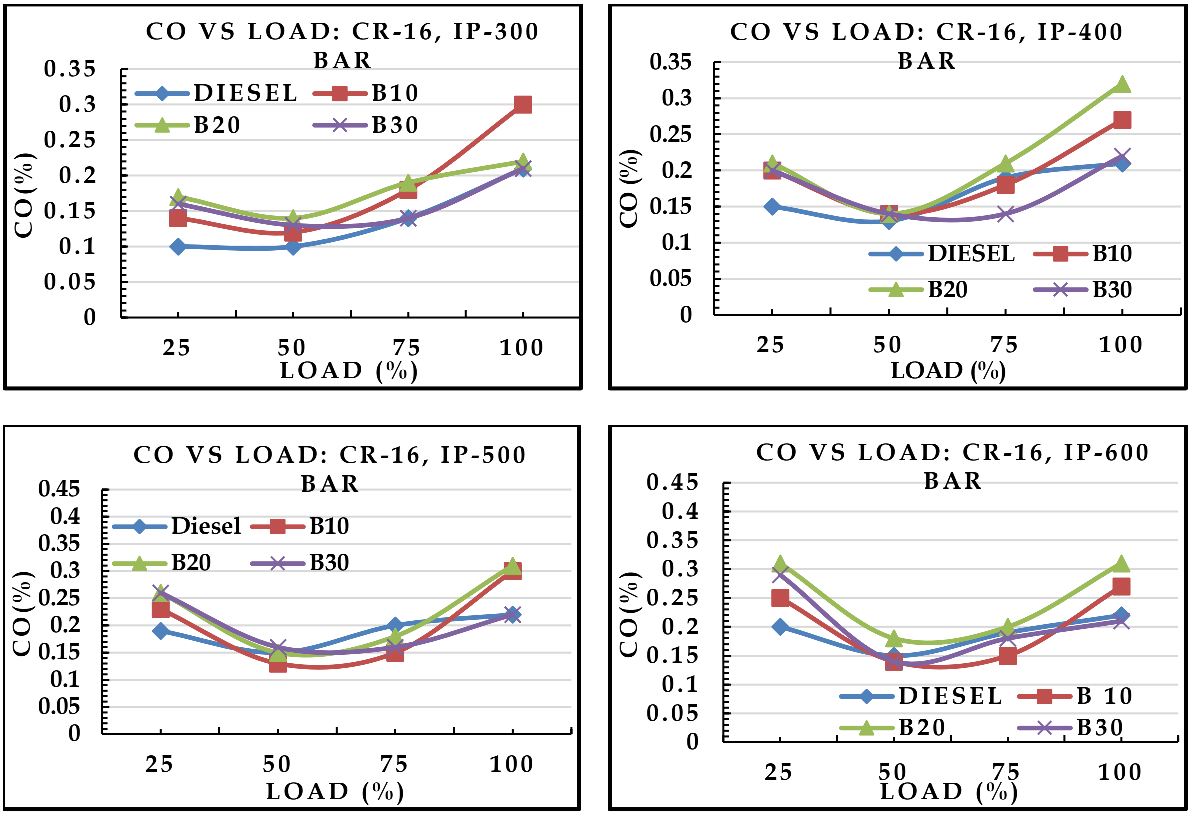


Figure 4-6: Variation in CO emission with load at CR 16

The generation of carbon monoxide increases as the load exceeds 50% and reaches full load due to a higher injection of fuel and a more uneven distribution, leading to inadequate mixing. The 0.1 % vol of lowest level of carbon monoxide emissions was observed at CR 17, IP 300 bar with a 50% load for the B10 blend, in comparison to the B0 (diesel), B20, and B30 blends. The presence of oxygen molecules in the biodiesel led to a decrease in the creation of carbon monoxide in the cylinder, as they were able to commence complete combustion. Under the conditions of CR 17, IP 300 bar, and less than 50% load, the carbon monoxide emissions for diesel, B10, B20, and B30 are 0.10%, 0.10%, 0.15%, and 0.11%, respectively.

Figure 4-8 represents the levels of carbon monoxide (CO) emissions from the tested fuel blends (B0, B10, B20, and B30) at varied injection pressures (300, 400, 500, and 600 bar) and compression ratio 18, across a range of load circumstances from 25% to 100%. At a load of 25%, the rise in the percentage of blend leads to a corresponding increase in CO emissions at all injection pressures compared to diesel fuel. This is mostly due to the kinematic viscosity and lower heating value of biodiesel blends.

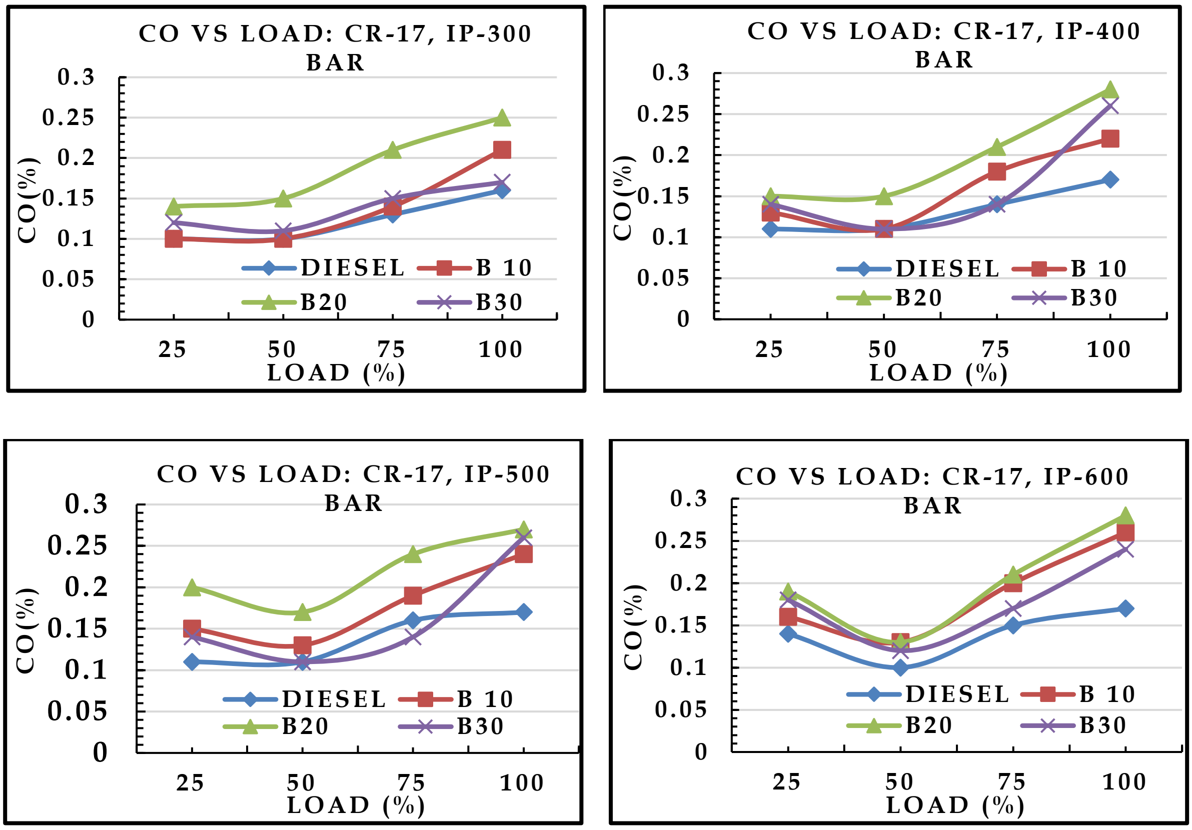


Figure 4-7:Variation in CO emission with load at CR 17

Under full load conditions, the CO emission increases for all the tested fuel blends due to the need for a higher fuel-air mixture to accommodate the maximum load. This leads to an uneven distribution and poor mixing.

Summary of Carbon monoxide emission (CO)

As the load intensifies, the emission of CO from the exhaust gas initially falls and subsequently increases under full load conditions. At low loads, the gas temperature inside the engine cylinder stays low, leading to incomplete combustion in the gas phase and a comparatively high emission of carbon monoxide.

As the load on the engine grows, the emission of carbon monoxide (CO) decreases. This is because the higher temperature of the gas inside the cylinder leads to an increased rate of oxidation of CO.

Under full load conditions, the CO emission increases for all the fuel blends with respect to the diesel fuel. The highest increment in CO emission of 128% with respect to diesel fuel vol observed for CR 18, IP 400 bar in case of B30 fuel blends.

This is due to the need for a larger fuel-air mixture to meet the maximum load condition.

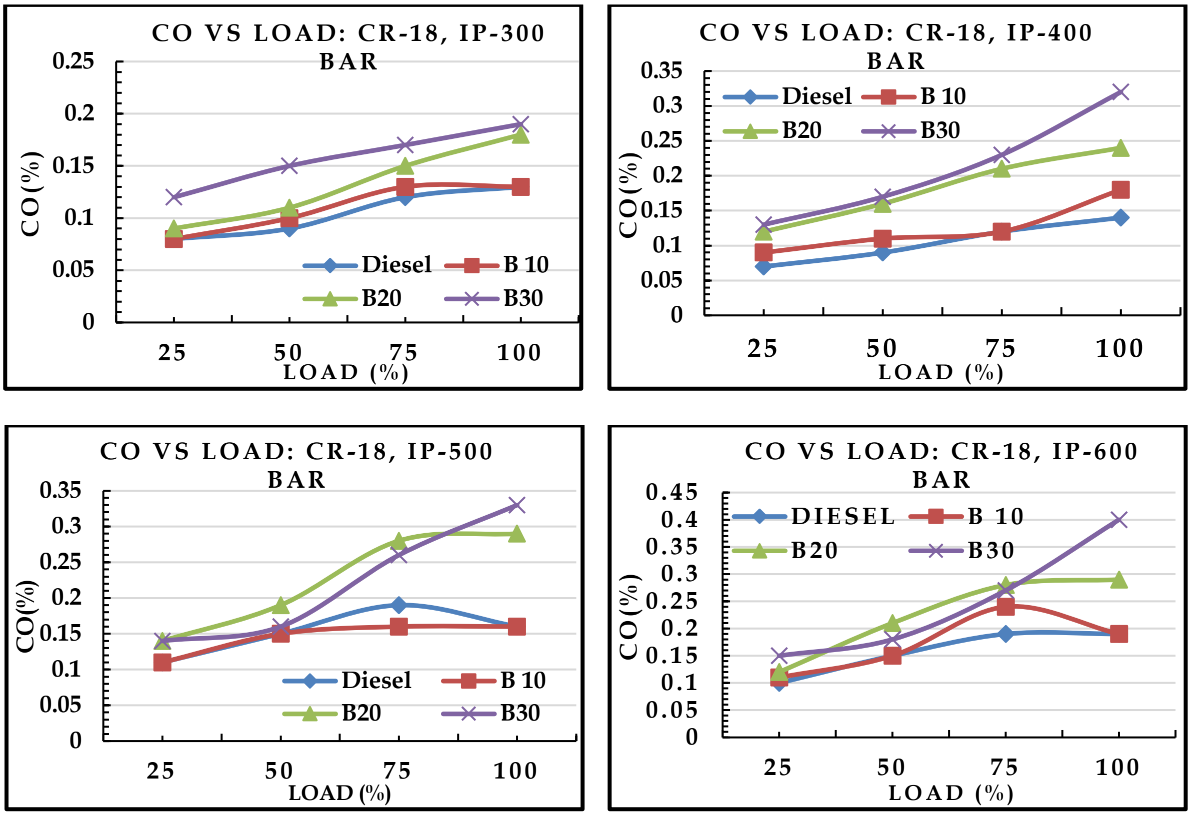


Figure 4-8:Variation in CO emission with load at CR 18

However, this increased mixture distribution is uneven, leading to poor mixing. The impact of different compression ratios on carbon monoxide emissions is more significant in comparison to injection pressure and the amount of biodiesel in the mixture. As the amount of biodiesel in the fuel blend increases, the impact on CO emissions is not consistent due to two conflicting factors: (i) the inferior atomization characteristics and volatility of biodiesel compared to diesel, and (ii) the presence of oxygen in biodiesel, which enhances the availability of oxygen from the air.

4.1.4 Unburned Hydrocarbon (UHC)

Unburned hydrocarbon emissions from the engine occur as a result of reduced temperatures within the engine cylinder and incomplete combustion of fuel vapor. Figure 4-9 illustrates the levels of hydrocarbon emissions for the tested fuel blends (B0, B10, B20, and B30) at varied injection pressures (300, 400, 500, and 600 bar) and compression ratio of 15, across a range of load circumstances from 25% to 100%. The investigations revealed that there is a direct correlation between the increase in fuel blend and the rise in HC emissions at compression ratio 15, specifically while operating at a 25% load. Under full load, the B10 fuel blend exhibits the lowest hydrocarbon emission of 37 ppm among all the tested fuel blends at a compression ratio (CR) of 15 and an injection pressure of 500 bar.

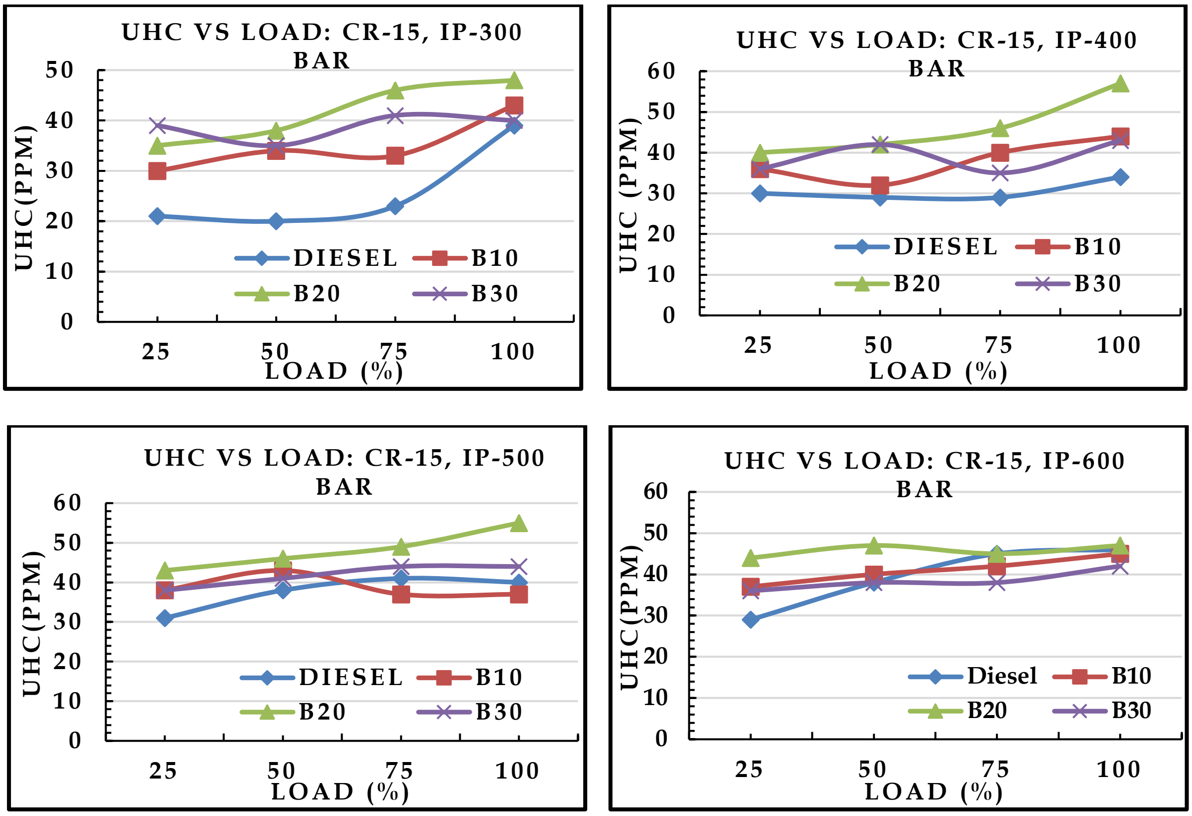


Figure 4-9:Variation in HC emission with load at CR 15

Comparatively, the B30 fuel blend exhibited the lowest HC emission level of 42 ppm, in contrast to diesel (47 ppm), B10 (46 ppm), and B20 (45 ppm). The HC emissions of the B10, B20, and diesel blends were respectively 10.66%, 8.69%, and 6.66% higher than the B30 mix. These tests were taken at CR 15 IP 600 bar at full load conditions. Biodiesel blends have a reduced UHC emission in comparison to diesel fuel due to the presence of oxygen molecules that actively participate in the combustion process. The presence of oxygen in the blend leads to complete combustion. At maximum load, UHC emissions are higher for all tested gasoline blends because more fuel is injected to compensate for the increased load. Figure 4-10 indicates the concentrations of unburned hydrocarbon emissions for the tested fuel blends (B0, B10, B20, and B30) at varied injection pressures (300, 400, 500, and 600 bar) and at a compression ratio of 16, while subject to varying load ranging from 25% to 100%. Based on the trials, it was noted that the rise in load leads to a corresponding increase in HC emissions at a compression ratio of 16 for all injection pressures. The biodiesel blends exhibited lower emissions of unburned hydrocarbons when compared to diesel fuel at compression ratio 16 and all injection pressure, across all load circumstances. The highest HC emission of 55 ppm recorded in case of diesel fuel for injection pressure 300 bar and 600 bar.

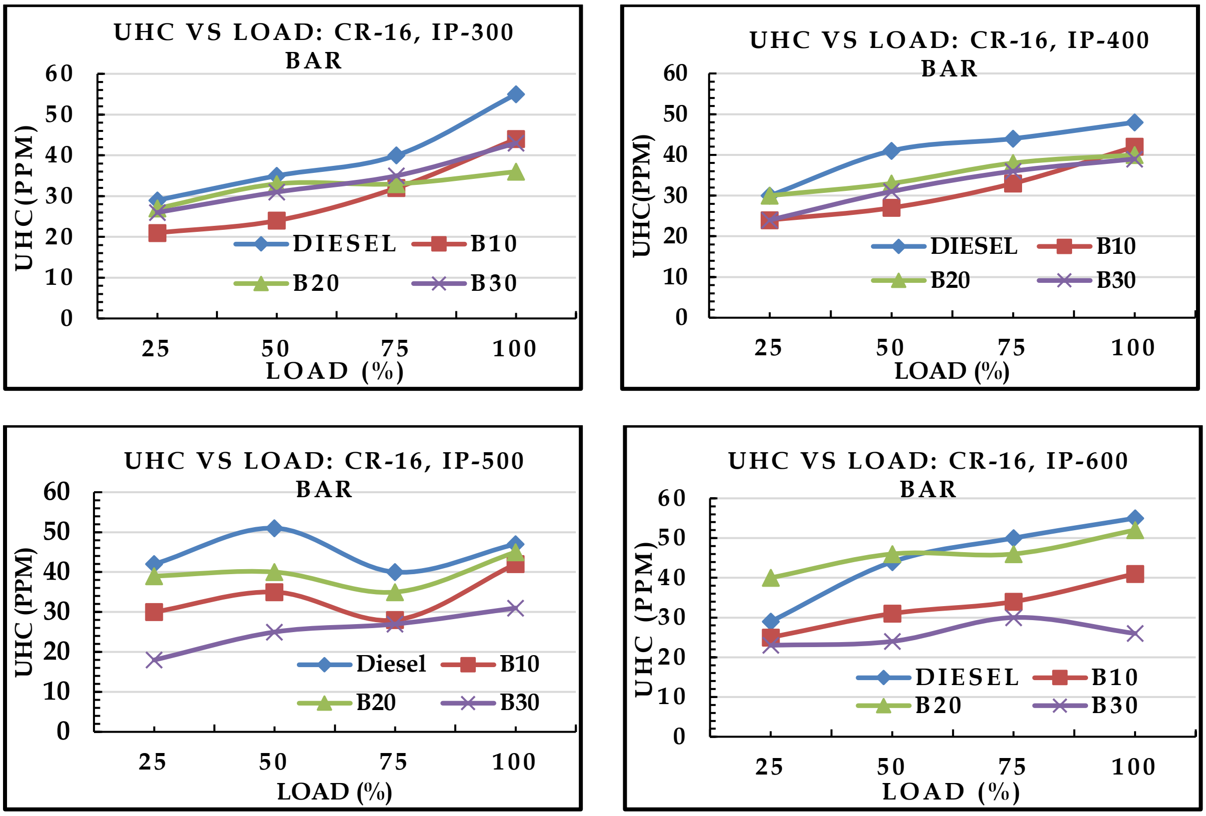


Figure 4-10:Variation in HC emission with load at CR 16

The presence of oxygen molecules in biodiesel enhances complete combustion during the combustion process. Under a 25% load, the B30 blend, with a CR (compression ratio) of 16 and ignition pressure of 500 bar, has the lowest UHC (unburned hydrocarbon) emission of 18 ppm. In comparison, diesel emits 42 ppm, B10 emits 30 ppm, and B20 emits 39 ppm. Under full load conditions, the studied fuel blends exhibit higher levels of HC emissions. This is attributed to the increased fuel injection caused by the richer mixture, which serves to offset the higher load. Among the evaluated fuel blends, the B30 blend exhibits the lowest emission at CR-16, IP-600 bar, surpassing the emissions of other blends, even the 25% load. Figure 4-11 exhibits the unburned hydrocarbon emissions for the fuel blends (B0, B10, B20, and B30) that were evaluated at varied injection pressures (300, 400, 500, and 600 bar) and compression ratio 17. The emissions were measured under different load conditions ranging from 25% to 100%. The trials demonstrated that all biodiesel blends exhibited lower UHC emissions than diesel fuel at CR 17 at injection pressures of 300, 400, and 600 bar, across all load circumstances. The highest HC emission of 57 ppm recorded in case of diesel fuel for injection pressure 300 bar.

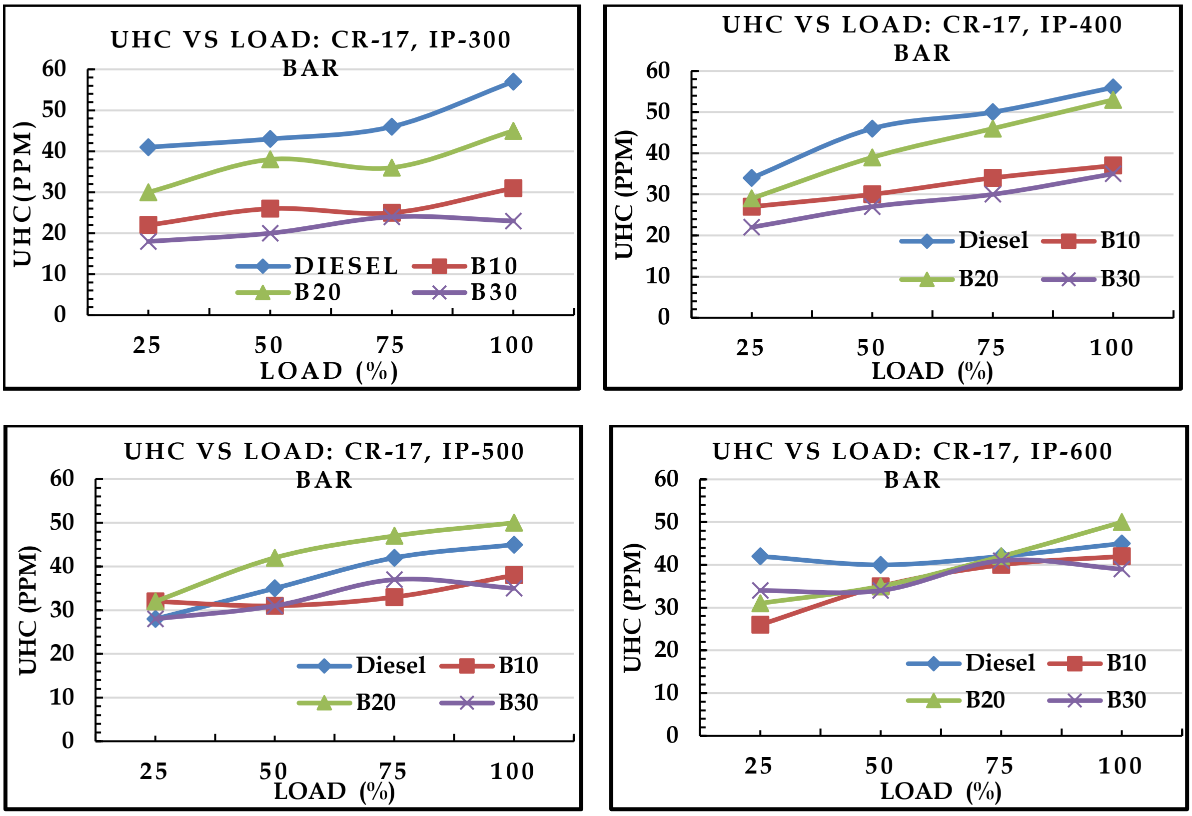


Figure 4-11:Variation in HC emission with load at CR 17

The presence of oxygen molecules in biodiesel facilitates full combustion, leading to its efficient utilization as a fuel source. As the load increases, the emission of unburned hydrocarbons similarly increases for a compression ratio (CR) of 17 for all injection pressures. During full load conditions, the studied fuel blends exhibited increased emissions of unburned hydrocarbons in comparison to lower loads. This is because, during full load, a larger amount of fuel is injected into the engine in order to compensate for the higher load, resulting in a richer mixture. Figure 4-12 exhibits the unburned hydrocarbon emissions for the fuel blends (B0, B10, B20, and B30) that were tested at varied injection pressures (300, 400, 500, and 600 bar) and compression ratio 18, while subject to varying load circumstances ranging from 25% to 100%. The trials revealed that diesel fuel exhibited greater unburned hydrocarbon emissions compared to all biodiesel mixes. This disparity can be attributed to the absence of oxygen molecules in diesel fuel, which are essential for achieving complete combustion. The UHC emission of the diesel fuel was higher (360 ppm) than that of all biodiesel blends at CR 18, IP 600 bar under full load conditions. The B20 blend exhibits the lowest level of UHC emissions, measuring at 26 ppm, when compared to diesel (235 ppm), B10 (37 ppm), and B30 (28 ppm) with a compression ratio of 18, injection pressure of 600 bar, and operating at 25% load.

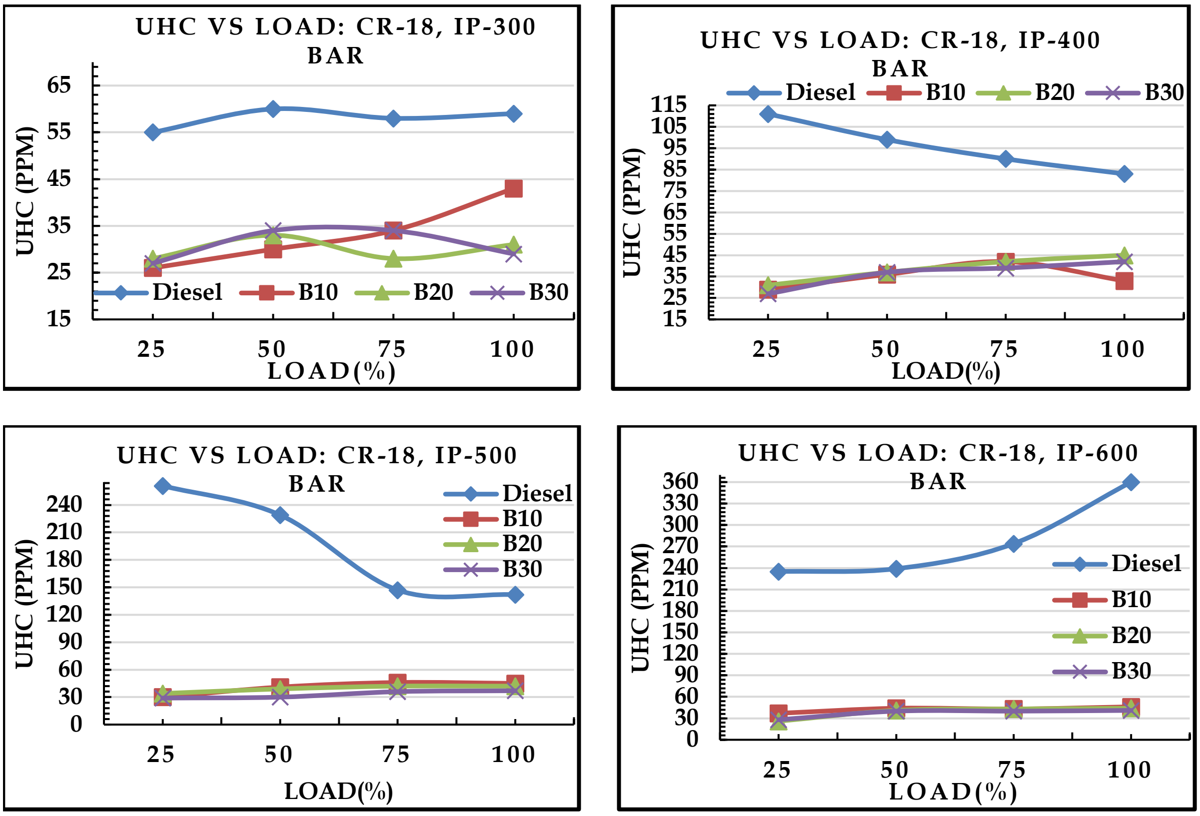


Figure 4-12:Variation in HC emission with load at CR 18

Under maximum load conditions, the emissions of unburned hydrocarbons are elevated for all the fuel blends that were tested due to the increased fuel consumption necessary to meet the higher load.

Summary of HC Emission

The emission of unburned hydrocarbons is directly proportional to the load, as the amount of fuel injected also increases with higher loads. During full load conditions, the studied fuel blends exhibited increased emissions of unburned hydrocarbons (UHC) in comparison to lower loads. This is because, during full load, a larger amount of fuel is injected into the engine to compensate for the higher load, resulting in a richer mixture. Comparatively, all biodiesel blends exhibited reduced UHC emissions in comparison to diesel fuel across various injection pressures and compression ratios, with the exception of CR 15 throughout all load circumstances. The highest hydrocarbon emissions in all the test runs were 360 ppm for the diesel fuel at an injection pressure (IP) of 600, and 57 ppm for the B20 fuel blend at an IP of 400 bar under full load conditions. The rationale behind this is that biodiesel possesses a higher cetane number and incorporates oxygen molecules that actively participate in combustion, thereby ensuring complete combustion.

4.1.5 Nitrogen Oxide (NOx) Emissions

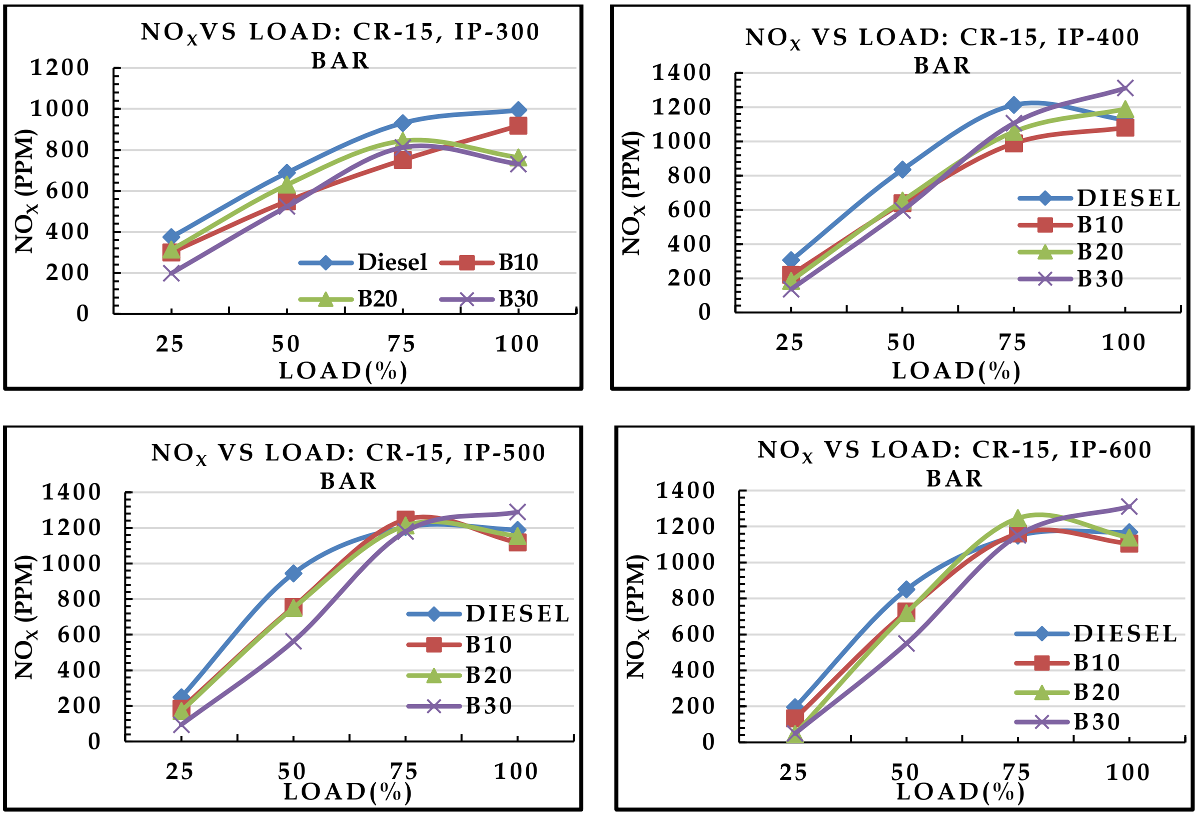


Figure 4-13:Variation in NOx emission with load at CR 15

Figure 4-13 illustrates the relationship between NOx emission and engine loads and IP at a compression ratio of 15 and a constant speed of 1500 rpm. The generation of NOx in the diesel engine mostly relies on the elevated gas temperature during the last stage of combustion and the quantity of oxygen molecules in the fuel. As the load rises from low load to 75% load, there is a corresponding increase in NOx emission due to the greater combustion of fuel, leading to a higher in-cylinder temperature. Once the load exceeds 75% and continues to increase, the emission of NOx begins to decline. This is due to the fact that at 75% load, the temperature within the cylinder reaches its peak, and any further increase in load does not result in a rise in temperature. Consequently, the emission of NOx starts to drop. Under lower loads, the combination of lean fuel-air mixing and reduced fuel consumption causes a decrease in the temperature inside the cylinder, leading to lower levels of NOx emissions. Under increased loads, the combination of excessive fuel and air mixture and elevated fuel consumption results in elevated temperatures within the combustion chamber, leading to increased levels of nitrogen oxides. At lower loads, biodiesel blends exhibit reduced NOx emissions in comparison to diesel fuel due to biodiesel's elevated viscosity, which hinders complete combustion and efficient mixing, thereby leading to a decrease in in-cylinder temperature.

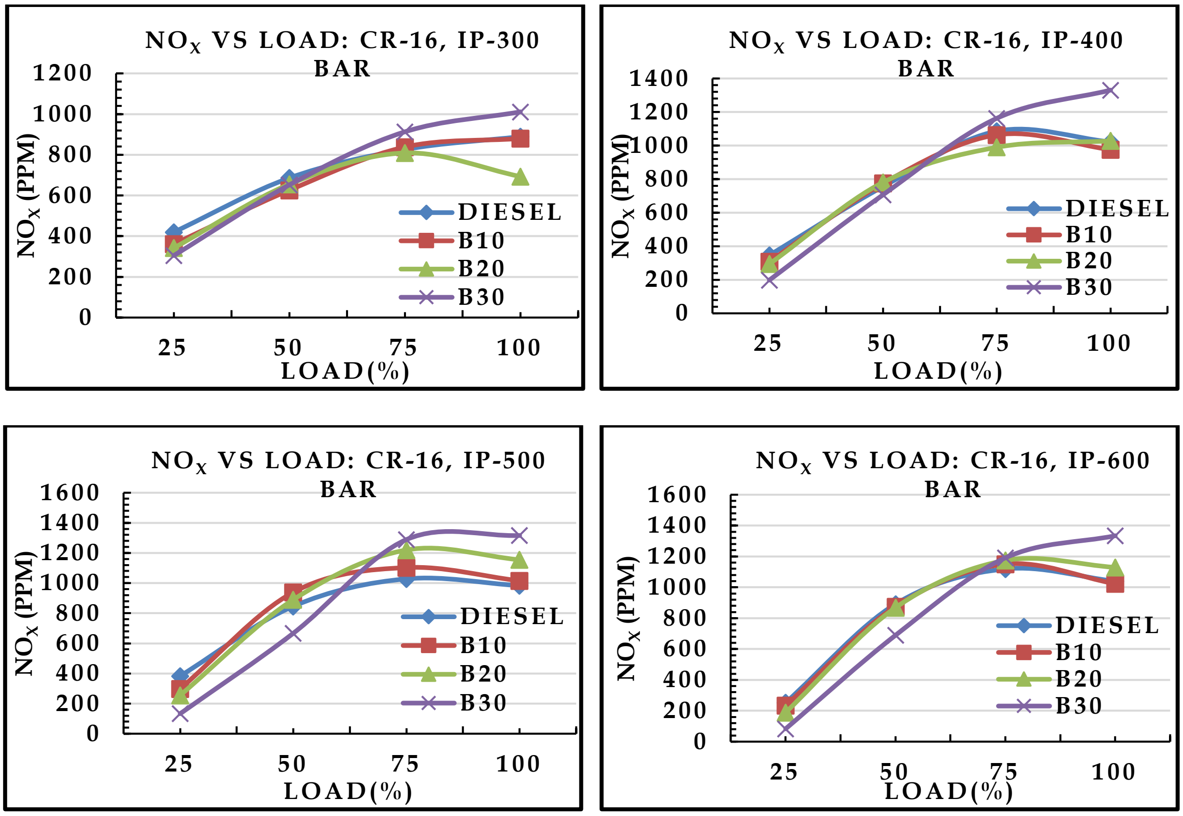


Figure 4-14:Variation in NOx emission with load at CR 16

The compression ratio of 15 and injection pressure of 600 bars resulted in NOx (nitrogen oxide) emissions of 375, 300, 313, and 198 ppm for B10, B20, B30, and diesel fuels, respectively. Under increased load and at an injection pressure of 600 bar, the B30 blend exhibits a 12.24% increase in NOx emissions compared to diesel fuel. This is attributed to the higher oxygen content in the B30 blend, which promotes more thorough combustion. Elevated temperatures within the combustion chamber result in increased levels of nitrogen oxide emissions. The increase in injection pressure led to an increase in NOx emissions due to the formation of a finer spray and improved atomization. This, in turn, resulted in a decrease in the time it takes for ignition to occur, leading to more efficient and thorough combustion at higher engine loads.

Figure 4-14 illustrates the relationship between NOx emission and engine loads and IP at a compression ratio of 16 and a constant speed of 1500 rpm. As the load percentage rises from low to 75%, there is a corresponding increase in NOx emissions due to the greater combustion of fuel, resulting in higher in-cylinder temperatures. However, above 75%, the creation of NOx begins to decline. At lower loads, biodiesel blends exhibit reduced NOx emissions compared to diesel fuel due to their increased viscosity, which hinders complete combustion and proper mixing, thereby lowering the temperature within the engine cylinder. At a compression ratio of 16 and an injection pressure of 600 bar, biodiesel blends B10, B20, and B30 exhibited reduced nitrogen oxide emissions of 233, 189, and 89 ppm respectively, in comparison to diesel fuel which emitted 252 ppm. However, at higher loads and the same IP of 600 bar, the B30 blend resulted in 9.14% higher NOx emissions than diesel fuel. This increase was attributed to the higher oxygen content in the B30 blend, which facilitated complete combustion. Elevated temperatures within the cylinder result in increased NOx emissions. Under full load conditions, diesel fuels with B10, B20, and B30 blends emit NOx emissions of 1039, 1023, 1129, and 1334 ppm at CR 16 and IP 600 bar.

Figure 4-15 illustrates the NOx emission variation for various engine loads and IP at a compression ratio of 17 and a constant speed of 1500 rpm. As the load increases from low load to 75% load, the emission of NOx likewise increases due to the increased combustion of fuel, leading to higher in-cylinder temperature. However, above 75% load, the generation of NOx begins to decrease. At lower loads, biodiesel blends (B20 and B30) exhibit reduced NOx emissions compared to diesel fuel due to biodiesel's higher viscosity, which hinders complete combustion and proper mixing. This leads to a lower temperature within the combustion chamber. However, the B10 blend demonstrated higher NOx emissions at compression ratio 17 and injection pressure levels of 400, 500, and 600 bar. At a compression ratio of 17 and an injection pressure of 600 bar, it was observed that the biodiesel blend B30 had 36.59% lower nitrogen oxide emissions (298 parts per million) compared to diesel fuel (470 parts per million). However, at higher loads and the same injection pressure of 600 bar, the B30 blend resulted in 17.16% higher NOx emissions compared to diesel fuel. This can be attributed to the presence of nitrogen in biodiesel derived from vegetable oil and its higher oxygen content, which leads to complete combustion at a higher temperature within the engine cylinder and consequently higher NOx emissions.

Under full load conditions, diesel fuels with B10, B20, and B30 blends produce NOx emissions of 1134, 1130, 1289, and 1324 ppm at CR 17 and IP 600 pressure. The B30 blend, operating at a compression ratio of 17 and an injection pressure of 300 bar, exhibited the lowest level of NOx emissions (806 ppm) compared to all other gasoline blends tested at maximum load conditions.

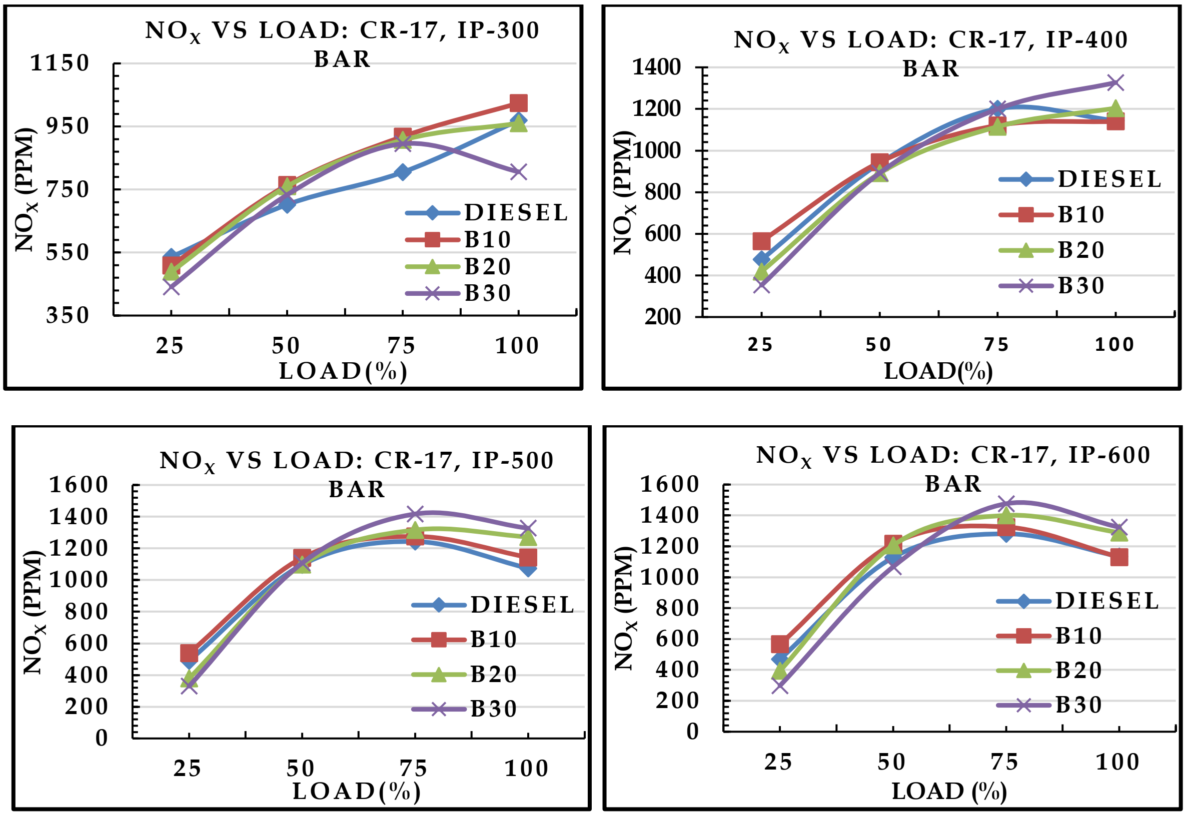


Figure 4-15:Variation in NOx emission with load at CR 17

Figure 4-16 illustrates the correlation between NOx emission and engine loads and IP at a compression ratio of 18 and a constant speed of 1500 rpm. As the load increases from low load to 75% load, there is a corresponding increase in NOx emissions due to the increased combustion of fuel, resulting in higher in-cylinder temperatures. However, above 75% load, the formation of NOx begins to decrease. At lower loads, biodiesel blends with 30% biodiesel content (B30) exhibit lower nitrogen oxide (NOx) emissions compared to diesel fuel. This is due to the increased viscosity of biodiesel, which causes incomplete combustion and inadequate mixing. As a result, the in-cylinder temperature is lower, leading to reduced NOx emissions. However, at compression ratios of 18 and injection pressures of 400 and 500 bar, blends with 10% biodiesel content (B10) showed higher NOx emissions. At a compression ratio of 18 and an injection pressure of 600 bar, the biodiesel blend B20 exhibited a 37.43% increase in NOx emissions (1953 ppm) compared to diesel fuel (1421 ppm) under a load of less than 75%. Similarly, at higher load and IP 600 bar, biodiesel blend B10 resulted in a 34.11% increase in NOx emissions compared to diesel fuel. This can be attributed to the presence of nitrogen in biodiesel derived from vegetable oil, as well as its higher oxygen content. These factors contribute to a higher in-cylinder temperature and subsequently higher NOx emissions due to complete combustion.

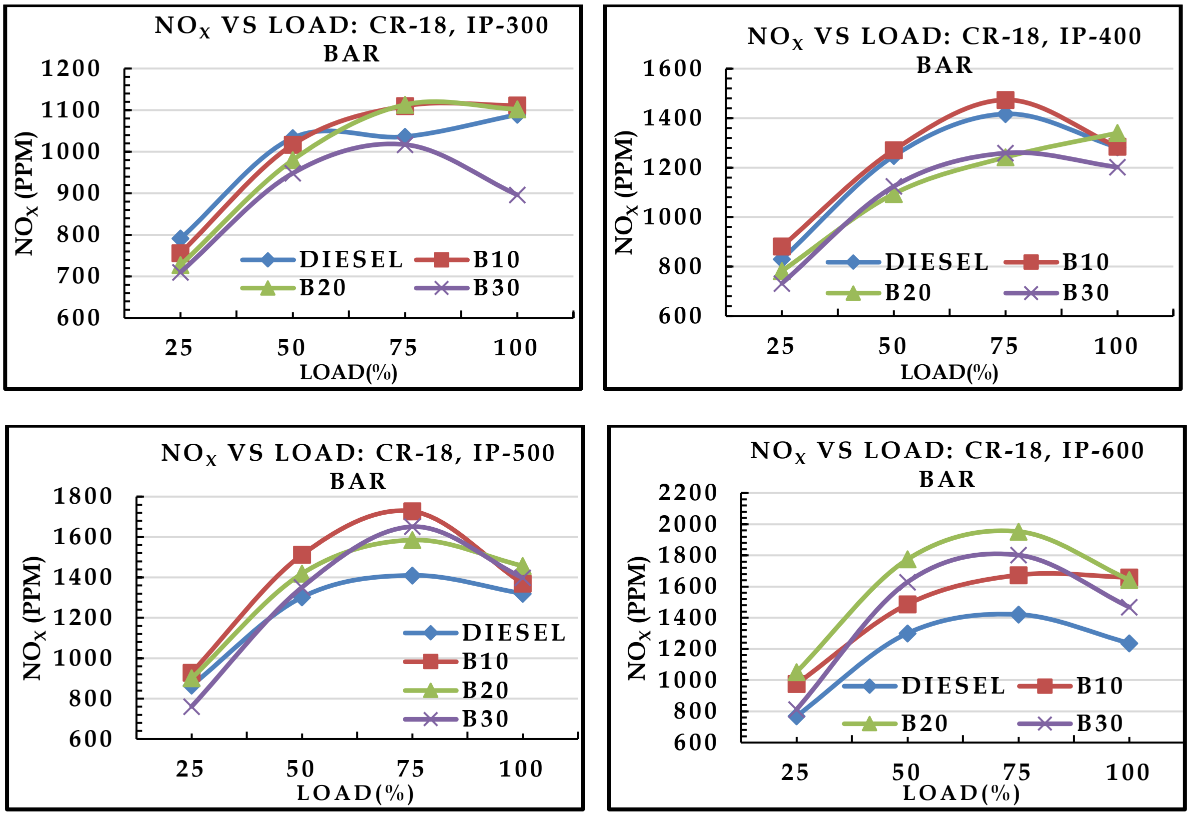


Figure 4-16:Variation in NOx emission with load at CR 18

Under 75% load conditions, diesel fuels with B10, B20, and B30 yield NOx emissions of 1421, 1674, 1953, and 1802 parts per million (ppm) at a compression ratio of 18 and an injection pressure of 600 bar. The B30 blend, operating at a compression ratio of 18 and an injection pressure of 300 bar, exhibited the lowest level of NOx emissions (896 ppm) compared to all other fuel blends tested at maximum load conditions.

Summary of NOx Emission

The generation of NOx in the diesel engine is primarily influenced by the elevated gas temperature during the final stage of combustion and the quantity of oxygen molecules in the fuel. As the load increases from low load to 75% load, there is a corresponding increase in NOx emissions due to the increased combustion of fuel, resulting in higher in-cylinder temperatures. However, above 75% load, the formation of NOx begins to decrease. At lower loads, biodiesel blends exhibit reduced NOx emissions compared to diesel fuel due to their increased viscosity, which hinders complete combustion and proper mixing, leading to a decrease in in-cylinder temperature. Under increased loads, the biodiesel mix releases a greater amount of nitrogen oxides in comparison to diesel. This is because biodiesel derived from vegetable oil contains nitrogen and has a higher oxygen content, leading to complete combustion and consequently, elevated in-cylinder temperatures and increased NOx emissions. The increase in compression ratio leads to higher NOx emissions as a result of the elevated temperature and pressure within the combustion chamber. The increase in injection pressure led to an increase in NOx emissions due to the formation of a fine spray and effective atomization. This, in turn, resulted in a decrease in ignition delay and improved combustion efficiency at higher loads.

Table 4-17: Maximum value of NOx emission for different parameters

NO_x	**Value (ppm)**	**Fuel Blend**	**Compression Ratio**	**Injection Pressure (bar)**	**Load (%)**
Maximum	1311	B30	15	600	100
Maximum	1334	B30	16	600	100
Maximum	1476	B30	17	600	75
Maximum	1958	B20	18	600	75

Table 4-17 provides a summary of the NOx emissions generated for different combinations of parameters. The B20 blend at CR 18 and IP 600 bar under 75% load has a maximum NOx emission of 1958 ppm, which is 37.43% higher than the diesel fuel under the same conditions. Among all the tested fuel blends, the B20 blend at CR 18 and IP 600 bar under 25% load has the minimum NOx emission of 46 ppm.

4.1.6 Smoke Opacity

Smoke opacity is the measurement of the quantity of smoke emitted from the exhaust of a CI engine. Figure 4-17 depicts the changes in smoke opacity under various load circumstances for different fuel blends and diesel fuel. The measurements were taken at varied injection pressures, namely at CR 15, and a constant speed of 1500 rpm. The smoke opacity rose proportionally with the rise in load, as a result of injecting more fuel to compensate for the greater load. As the load transitions from low to 75%, there is a progressive increase in smoke opacity. However, while testing various fuel mixes and diesel fuel, there is a dramatic jump in smoke opacity from 75% to 100% engine load. This phenomenon can be attributed to the insufficient presence of oxygen resulting from the chemical interaction between nitrogen and oxygen at elevated combustion temperatures. Furthermore, smoke is being generated in the fuel-rich region of the cylinder as a result of elevated temperature and pressure, which is caused by a lack of oxygen. When the load is reduced, B10 and B20 blends produce more smoke opacity than diesel fuel. An increase in smoke opacity at higher loads has been recorded for all biodiesel blends compared to diesel fuel at a compression ratio of 15 and all injection pressures.

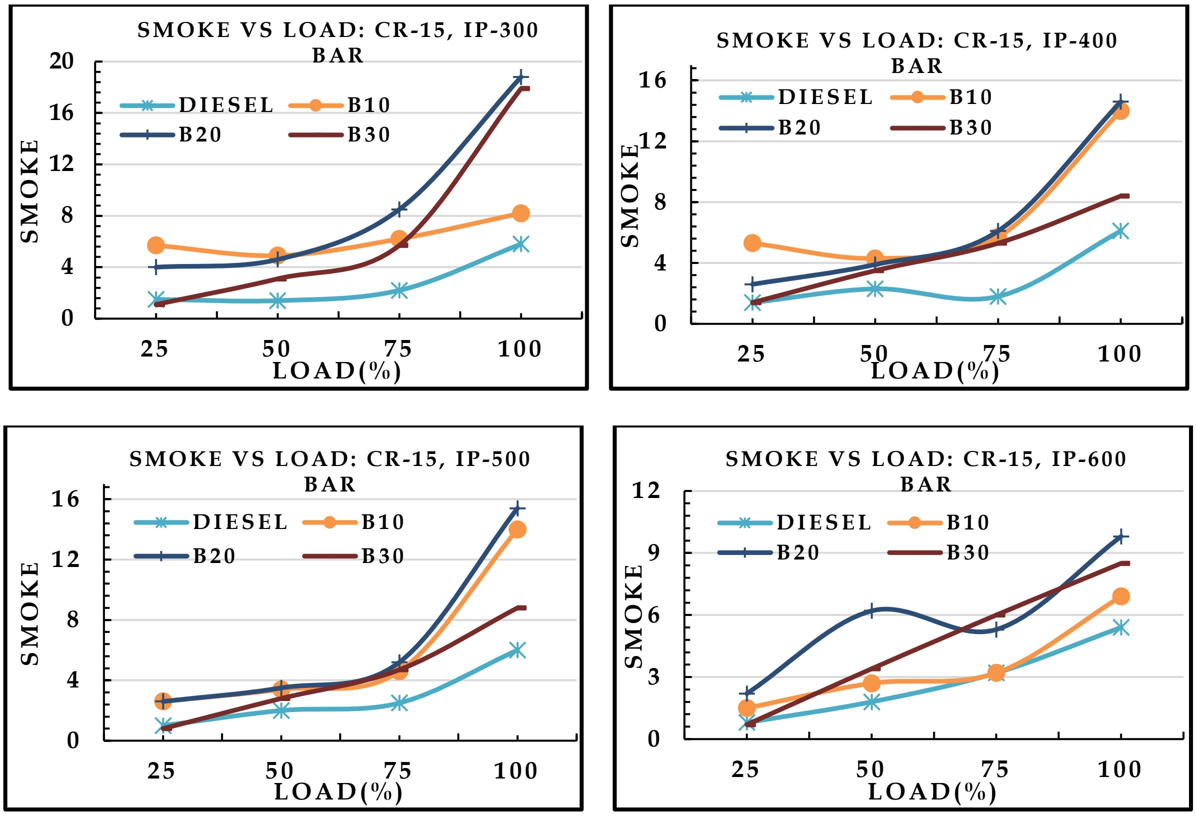


Figure 4-17:Variation in Smoke emission with load at CR 15

Figure 4-18 shows the changes in smoke opacity under various load circumstances for different fuel blends and diesel fuel, with varying injection pressures at a compression ratio of 16 and a constant speed of 1500 rpm. The smoke opacity escalated proportionally with the load augmentation, as a result of injecting a greater amount of fuel to counterbalance the elevated load. As the load transitions from low to 75%, there is a steady increase in smoke opacity. Subsequently, there is a dramatic increase in smoke opacity as the load goes from 75% to 100% for all the fuel blends evaluated, as well as for diesel fuel. The abrupt increase could be attributed to a chemical interaction occurring between nitrogen and oxygen under elevated combustion temperatures. During peak load, a greater amount of fuel is necessary, hence a fuel-air mixture with a higher concentration of fuel is provided in the cylinder. The smoke creation is a result of elevated temperatures and pressure, caused by a lack of oxygen. Figure 4-19 indicates the changes in smoke opacity under various load circumstances for different fuel blends and diesel fuel. These measurements were taken at varied injection pressures, namely at CR 17, and with a constant speed of 1500 rpm.

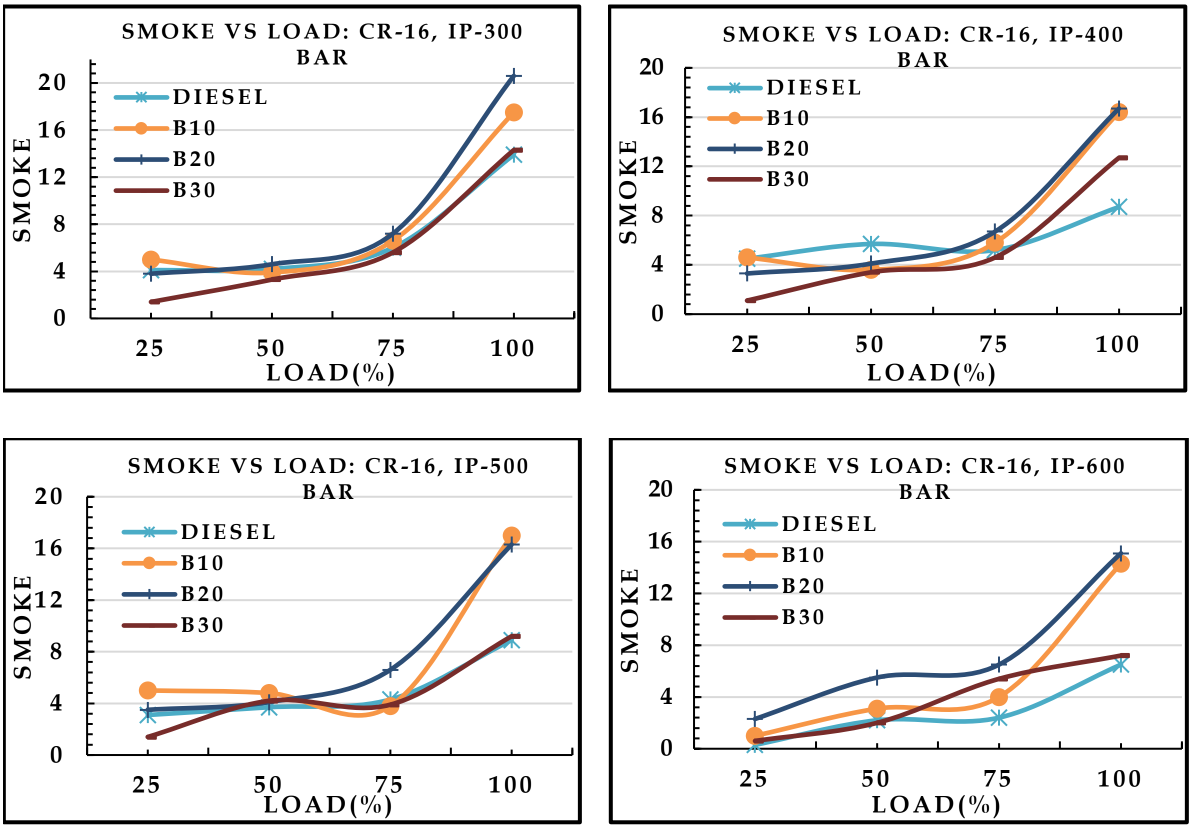


Figure 4-18:Variation in Smoke emission with load at CR 16

The smoke opacity rose in correlation with the load rise, as a result of injecting more fuel to counterbalance the elevated load. As the load increases from low to 75%, there is a gradual increase in smoke opacity. This is observed for all tested fuel blends as well as diesel fuel. Following this, there is a significant rise in smoke opacity when the load is increased from 75% to 100% for all the fuel mixes examined, including diesel fuel. The sudden rise can be ascribed to a chemical reaction taking place between nitrogen and oxygen at higher combustion temperatures. Under full load conditions, a greater amount of fuel is necessary, leading to the rich fuel within the cylinder. Smoke is being generated as a result of the elevated temperature and pressure caused by a lack of oxygen. At compression ratio 17 and injection pressure of 600 bar under full load, the B20 blend exhibits the lowest smoke opacity of 6.4 compared to diesel fuel (6.8), B10 blend (9), and B30 blend (8.5). Figure 4-20 illustrates the changes in smoke opacity under various load circumstances for different fuel blends and diesel fuel. The measurements were taken at varied injection pressures, with a compression ratio of 18 and a constant speed of 1500 rpm. The formation of smoke mostly results from the incomplete combustion of the fuel and the presence of unreacted carbon in the fuel.

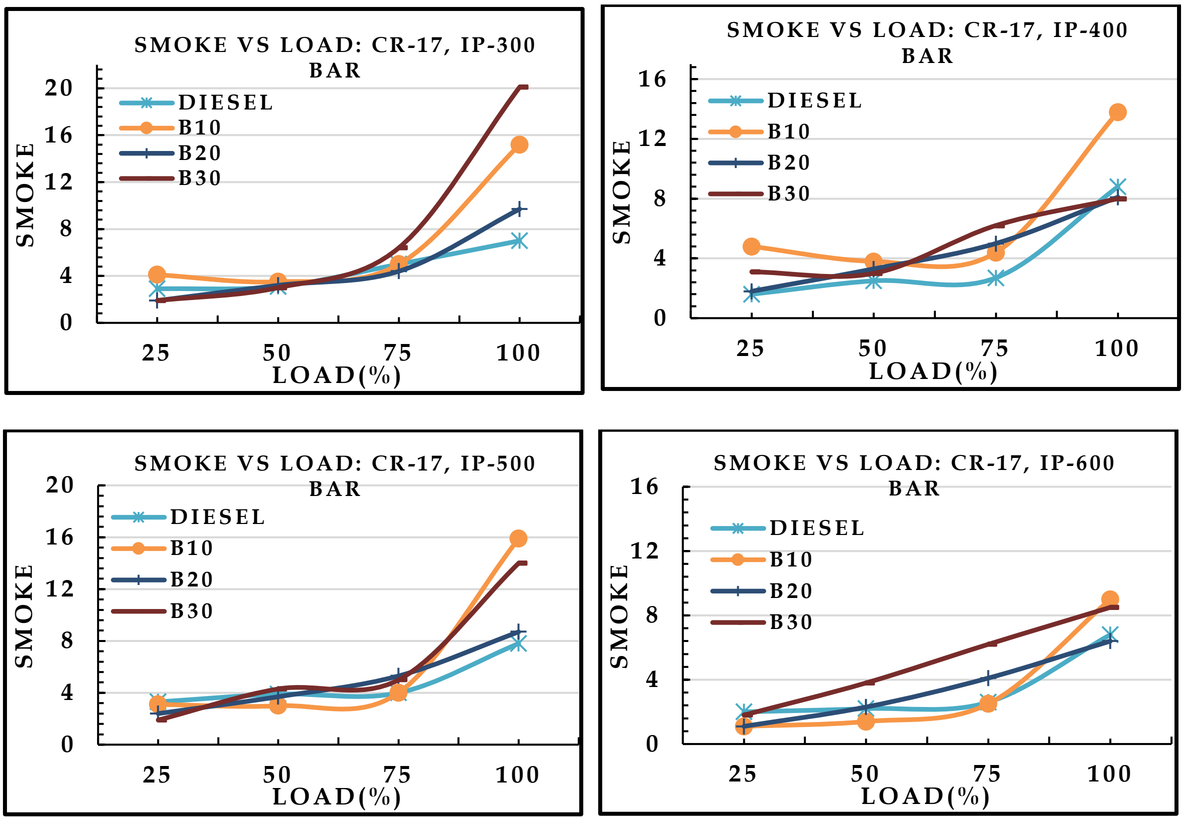


Figure 4-19:Variation in Smoke emission with load at CR 17

The increase in fuel injection pressure resulted in a decrease in the level of smoke opacity for all biodiesel blends in comparison to diesel fuel. Under increased pressure, the fuel is atomized into a spray and effectively mixed with oxygen, resulting in enhanced fuel oxidation and complete combustion. Under full load conditions, the smoke opacity decreased in all biodiesel blends compared to diesel fuel due to the decrease in the hydrocarbon ratio and the surplus of oxygen in the MLME biodiesel blend. At a compression ratio of 18 and an injection pressure of 600 bar, biodiesel blends B10 (4), B20 (6.8), and B30 (8.6) exhibit reduced smoke opacity compared to diesel fuel (16.7).

Summary of Smoke Emission

The smoke opacity increased due to a higher load, which caused the engine to inject additional fuel in order to compensate. The increase in fuel injection pressure resulted in a decrease in smoke opacity for all biodiesel blends when compared to diesel fuel. Under increased pressure, the fuel is dispersed into a fine mist and effectively mixed with oxygen, resulting in enhanced fuel oxidation and complete combustion.

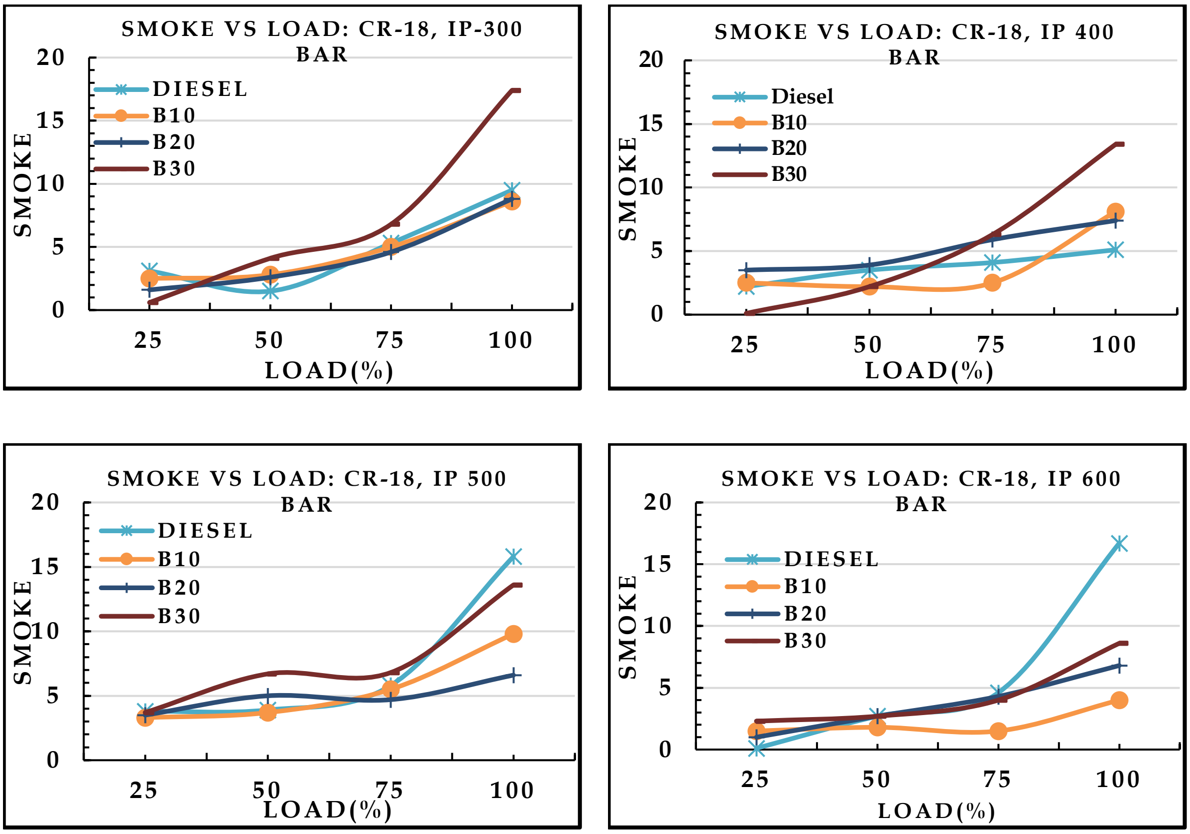


Figure 4-20:Variation in Smoke emission with load at CR 18

Under full load conditions, at higher compression ratio and injection pressure, the smoke opacity decreased in all biodiesel blends compared to diesel fuel. This can be attributed to the decrease in the hydrocarbon ratio and the surplus of oxygen in the MLME biodiesel mix. Nevertheless, the rise in fuel viscosity and inadequate volatility resulting from higher biodiesel concentrations in fuel blends result in suboptimal fuel mixing and spray. These two things have opposite effects.

Among all the tested fuel blends, the B20 blend produces the highest level of smoke (20.6) when tested at CR 16 and IP 300 pressure under full load conditions. On the other hand, when tested at CR 18 and IP 400 bar under 25% load, the B30 blend emits the lowest level of smoke (0.1) among all the tested fuel blends.

4.2 Operating Parameters for the Phase II Experimentation

The B20 blend produces a higher level of nitrogen oxide emissions, specifically 1953 ppm, when the compression ratio is 18 and the injection pressure

(IP) is 600 bar, while operating at 75% load. However, it emits the lowest level of NO_X, specifically 46 ppm, when the CR is 15 and the IP is 600 bar, while operating at 25% load. These emission levels are compliant with the BS-VI emission standard. At lower loads, biodiesel blends exhibit reduced NO_X emissions compared to diesel fuel due to their higher viscosity, which hinders complete combustion and proper mixing, consequently leading to a decrease in in-cylinder temperature. Under increased loads, the oxygen content in the mixture increases, leading to complete combustion. This, in turn, causes a significant rise in the temperature within the cylinder and results in higher emissions of nitrogen oxides. The increase in compression ratio leads to an increase in NOx emissions due to higher in-cylinder temperature and pressure. The increase in injection pressure led to an increase in NOx emission due to the formation of a fine spray and effective atomization. This, in turn, reduced the ignition delay and resulted in improved and more thorough combustion.

We have quantified the NOx emission at various combination of the operating parameters and the Table 4-17 shows the highest NOx emission recorded for each compression ratio. For each compression ratio, highest NOx is recorded for 600 bar injection pressure. The engine omits highest NOx emissions at 100% and 75% engine loading condition for various parameter combinations. So, for the second phase of experimentation, the decided operating parameters are shown in Table 3-11.of chapter 3.

4.3 Phase II Result and Discussion

4.3.1 Observations and Results

Table 4-18: Observations and Results for fuel blend B10, CR-18, IP-600 bar

B10, CR-18 IP-600 bar	Water injection timing (ms)	Flow rate of water (cc/min)	Emisisons			
Load(kg)			NOx ppm	HC ppm	CO % vol.	Smoke
9	0	0.0	1512	9	0.06	20
9	10	38.7	1401	13	0.05	7
9	20	82.7	1350	13	0.04	4.3
9	30	130.4	1245	14	0.04	3
9	35	166.7	1260	14	0.04	3
12	0	0.0	1624	16	0.09	30
12	10	38.7	1490	12	0.07	17.5
12	20	82.7	1423	17	0.05	7.2
12	30	130.4	1319	12	0.03	5.7
12	35	166.7	1306	15	0.03	6

Table 4-19:Observations and Results for fuel blend B10, CR-17, IP-600 bar

B10, CR-17 IP-600 bar	Water injection timing (ms)	Flow rate of water (cc/min)	Emissions			
Load(kg)			NOx ppm	HC ppm	CO % vol.	Smoke
9	0	0.0	1280	11	0.06	10
9	10	38.7	1176	11	0.04	4.6
9	20	82.7	1119	10	0.03	4.4
9	30	130.4	1068	8	0.03	3.3
9	35	166.7	1075	10	0.03	4.4
12	0	0.0	1196	12	0.05	23.5
12	10	38.7	1135	9	0.05	15
12	20	82.7	1050	12	0.05	7.2
12	30	130.4	999	11	0.03	5.4
12	35	166.7	1001	11	0.03	5.4

Table 4-20:Observations and Results for fuel blend B10, CR-16, IP-600 bar

B10, CR-16 IP-600 bar	Water injection timing (ms)	Flow rate of water (cc/min)	Emissions			
Load(kg)			NOx ppm	HC ppm	CO % vol.	Smoke
9	0	0.0	1108	12	0.08	13.7
9	10	38.7	1023	13	0.05	7.9
9	20	82.7	990	9	0.04	2.1
9	30	130.4	921	10	0.03	1.1
9	35	166.7	910	10	0.03	2
12	0	0.0	1055	11	0.06	9.8
12	10	38.7	974	8	0.05	8.1
12	20	82.7	926	9	0.04	6.8
12	30	130.4	884	5	0.03	6
12	35	166.7	900	9	0.03	7

Table 4-21:Observations and Results for fuel blend B10, CR-15, IP-600 bar

B10, CR-15 IP-600 bar	Water injection timing (ms)	Flow rate of water (cc/min)	Emissions			
Load(kg)			NOx ppm	HC ppm	CO % vol.	Smoke
9	0	0.0	1184	14	0.06	8.2
9	10	38.7	1101	10	0.05	6.2
9	20	82.7	1042	13	0.04	2.3
9	30	130.4	990	10	0.04	1.9
9	35	166.7	970	12	0.04	2.1
12	0	0.0	1154	14	0.07	18.9
12	10	38.7	1063	12	0.06	15
12	20	82.7	997	12	0.05	5.8
12	30	130.4	950	10	0.04	3.2
12	35	166.7	966	11	0.04	4.1

Table 4-22:Observations and Results for fuel blend B20, CR-18, IP-600 bar

B20, CR-18 IP-600 bar	Water injection timing (ms)	Flow rate of water (cc/min)	Emissions			
Load(kg)			NOx ppm	HC ppm	CO % vol.	Smoke
9	0	0.0	1521	14	0.06	19.3
9	10	38.7	1402	14	0.06	5.8
9	20	82.7	1356	12	0.04	5.6
9	30	130.4	1236	9	0.03	5.7
9	35	166.7	1252	12	0.03	5.1
12	0	0.0	1579	15	0.06	17.8
12	10	38.7	1438	14	0.05	8.6
12	20	82.7	1389	14	0.04	4.5
12	30	130.4	1309	9	0.03	4.9
12	35	166.7	1296	10	0.03	4.5

Table 4-23:Observations and Results for fuel blend B20, CR-17, IP-600 bar

B20, CR-17 IP-600 bar	Water injection timing (ms)	Flow rate of water (cc/min)	Emissions			
Load(kg)			NOx ppm	HC ppm	CO % vol.	Smoke
9	0	0.0	1302	13	0.06	19.3
9	10	38.7	1194	15	0.05	5.8
9	20	82.7	1120	4	0.03	5.6
9	30	130.4	1062	1	0.02	2.3
9	35	166.7	1080	1	0.02	3.2
12	0	0.0	1313	9	0.06	27
12	10	38.7	1211	8	0.06	19.7
12	20	82.7	1150	8	0.04	5.3
12	30	130.4	1054	8	0.04	7.5
12	35	166.7	1039	5	0.04	6

Table 4-24:Observations and Results for fuel blend B20, CR-16, IP-600 bar

B20, CR-16 IP-600 bar	Water injection timing (ms)	Flow rate of water (cc/min)	Emissions			
Load(kg)			NOx ppm	HC ppm	CO % vol.	Smoke
9	0	0.0	1144	10	0.06	7.4
9	10	38.7	1047	7	0.05	5.9
9	20	82.7	1015	1	0.04	1.7
9	30	130.4	938	9	0.04	3.6
9	35	166.7	961	5	0.04	3.1
12	0	0.0	1090	9	0.06	19.5
12	10	38.7	1009	4	0.06	17.1
12	20	82.7	959	2	0.05	5.3
12	30	130.4	892	10	0.04	4.9
12	35	166.7	915	6	0.04	3.1

Table 4-25:Observations and Results for fuel blend B20, CR-15, IP-600 bar

B20, CR-15 IP-600 bar	Water injection timing (ms)	Flow rate of water (cc/min)	Emissions			
Load(kg)			NOx ppm	HC ppm	CO % vol.	Smoke
9	0	0.0	1171	16	0.1	17.9
9	10	38.7	1077	13	0.07	7.3
9	20	82.7	1042	14	0.06	3.4
9	30	130.4	980	9	0.05	2.1
9	35	166.7	960	8	0.05	3.5
12	0	0.0	1183	15	0.09	16.8
12	10	38.7	1101	13	0.07	17.1
12	20	82.7	1054	10	0.07	4.3
12	30	130.4	960	9	0.07	3.2
12	35	166.7	977	8	0.07	2.8

Table 4-26:Observations and Results for fuel blend B30, CR-18, IP-600 bar

B30, CR-18 IP-600 bar	Water injection timing (ms)	Flow rate of water (cc/min)	Emissions			
Load(kg)			NOx ppm	HC ppm	CO % vol.	Smoke
9	0	0.0	1530	13	0.08	6.8
9	10	38.7	1405	12	0.06	5.9
9	20	82.7	1359	11	0.04	5.1
9	30	130.4	1237	10	0.04	4.7
9	35	166.7	1223	8	0.04	8
12	0	0.0	1409	13	0.06	30.3
12	10	38.7	1300	12	0.06	21.6
12	20	82.7	1214	10	0.05	15.7
12	30	130.4	1150	9	0.04	7
12	35	166.7	1131	5	0.04	8

Table 4-27:Observations and Results for fuel blend B30, CR-17, IP-600 bar

B30, CR-17 IP-600 bar	Water injection timing (ms)	Flow rate of water (cc/min)	Emissions			
Load(kg)			NOx ppm	HC ppm	CO % vol.	Smoke
9	0	0.0	1400	11	0.06	16.6
9	10	38.7	1274	11	0.05	5.5
9	20	82.7	1219	10	0.05	3.5
9	30	130.4	1144	9	0.04	2.6
9	35	166.7	1145	5	0.04	3.2
12	0	0.0	1318	14	0.06	24.5
12	10	38.7	1210	9	0.05	18.8
12	20	82.7	1136	13	0.04	7.3
12	30	130.4	1089	11	0.04	5.5
12	35	166.7	1101	10	0.04	4.9

Table 4-28:Observations and Results for fuel blend B30, CR-16, IP-600 bar

B30, CR-16 IP-600 bar	Water injection timing (ms)	Flow rate of water (cc/min)	Emissions			
Load(kg)			NOx ppm	HC ppm	CO % vol.	Smoke
9	0	0.0	1156	13	0.07	5.8
9	10	38.7	1053	11	0.06	4.9
9	20	82.7	1017	10	0.04	4.3
9	30	130.4	947	9	0.04	3.9
9	35	166.7	933	10	0.04	6.1
12	0	0.0	1310	15	0.09	27.4
12	10	38.7	1200	13	0.07	26.6
12	20	82.7	1143	9	0.07	7.1
12	30	130.4	1064	10	0.06	4.4
12	35	166.7	1072	11	0.06	5.3

Table 4-29:Observations and Results for fuel blend B30,CR-15, IP-600 bar

B30, CR-15 IP-600 bar	Water injection timing (ms)	Flow rate of water (cc/min)	Emissions			
Load(kg)			NOx ppm	HC ppm	CO % vol.	Smoke
9	0	0.0	1069	18	0.09	13
9	10	38.7	980	14	0.05	8.7
9	20	82.7	929	12	0.05	5.2
9	30	130.4	900	11	0.04	4.9
9	35	166.7	921	11	0.04	5.8
12	0	0.0	1265	15	0.08	24.7
12	10	38.7	1166	14	0.07	14.9
12	20	82.7	1092	13	0.06	6.1
12	30	130.4	1042	6	0.06	5.4
12	35	166.7	1066	5	0.06	4.8

4.4 Effect of Water Injection on Exhaust Emissions

Experimentally investigated the effect of water on exhaust emissions by injecting the water into the downstream of the test rig fueled with diesel biodiesel blends. The behavior of emissions elements like NOx, CO, HC and smoke is discussed as follows.

4.4.1 Water Injection Effect on NOx Emission

Oxides of nitrogen gas from an exhaust gas can be absorbed in aqueous solutions. The absorption process involves gas-phase and liquid-phase reactions and the diffusion of products and reactants take place. Overall, NO_X emission reacts with water to form nitric and nitrous acid.

Figure 4-21, Figure 4-22 and Figure 4-23 shows the behaviour of NOx emission with the rise of the water flow rate into the downstream of the engine.

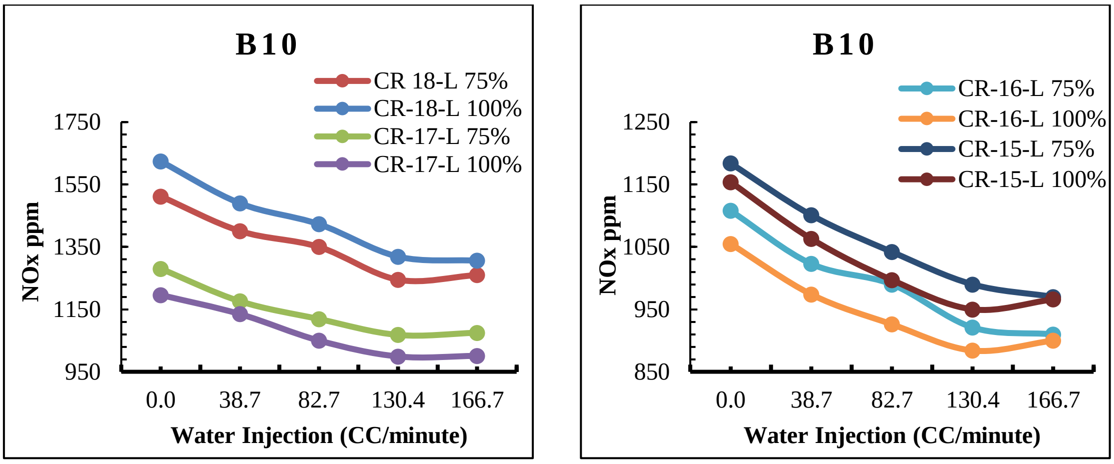


Figure 4-21:Effect of water injection on NOx emission for B10 Blend

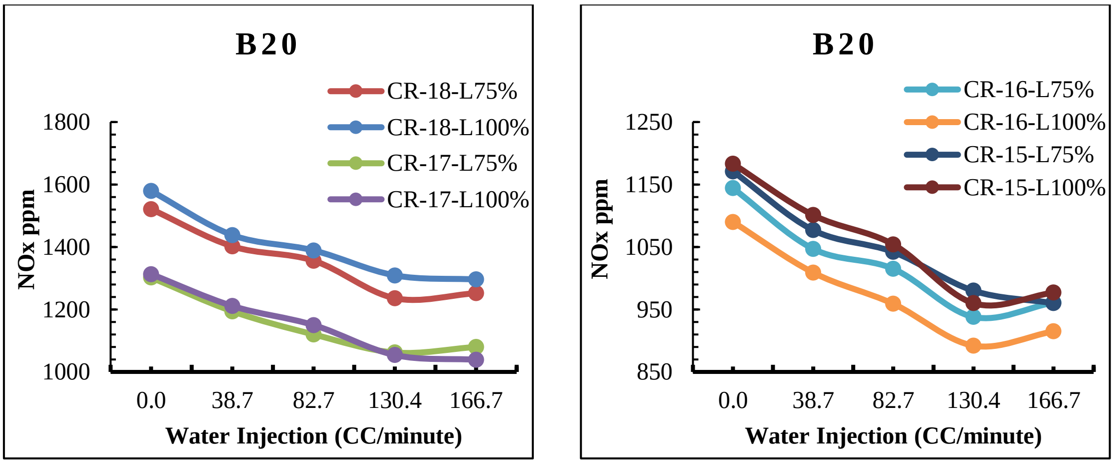


Figure 4-22:Effect of water injection on NOx emission for B20 Blend

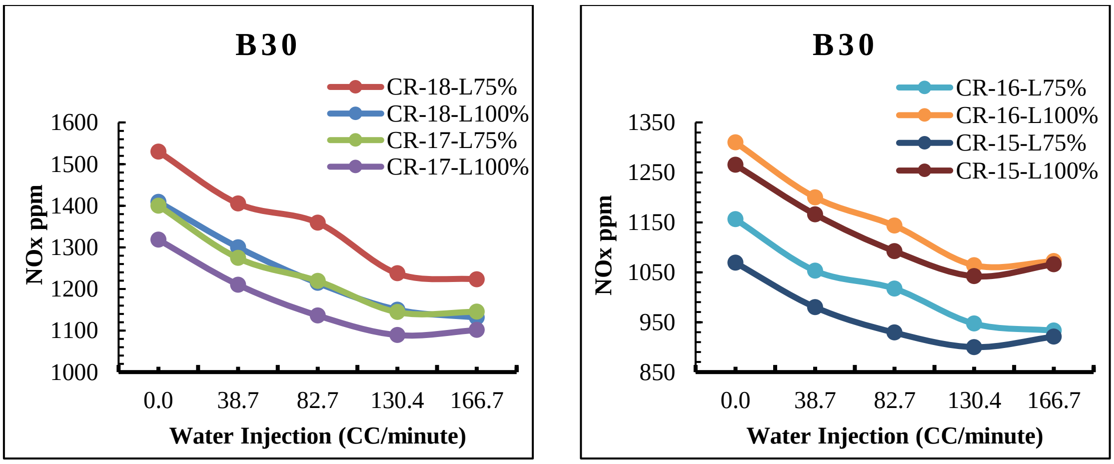


Figure 4-23:Effect of water injection on NOx emission for B30 Blend

Table 4-30:NOx emission reduction, water injection flow rate wise

Blend	CR	Load (%)	% Reduction in NOx			
			Water injection flow rate (cc/min)			
			38.7	82.7	130.4	166.7
B10	18	75	7.34	10.71	17.66	16.67
	18	100	8.25	12.38	18.78	19.58
	17	75	8.13	12.58	16.56	16.02
	17	100	5.10	12.21	16.47	16.30
	16	75	7.67	10.65	16.88	17.87
	16	100	7.68	12.23	16.21	14.69
	15	75	7.01	11.99	16.39	18.07
	15	100	7.89	13.60	17.68	16.29
B20	18	75	7.82	10.85	18.74	17.69
	18	100	8.93	12.03	17.10	17.92
	17	75	8.29	13.98	18.43	17.05
	17	100	7.77	12.41	19.73	20.87
	16	75	8.48	11.28	18.01	16.00
	16	100	7.43	12.02	18.17	16.06
	15	75	8.03	11.02	16.31	18.02
	15	100	6.93	10.90	18.85	17.41
B30	18	75	8.17	11.18	19.15	20.07
	18	100	7.74	13.84	18.38	19.73
	17	75	9	12.93	18.29	18.21
	17	100	8.19	13.81	17.37	16.46
	16	75	8.91	12.02	18.08	19.29
	16	100	8.40	12.75	18.78	18.17
	15	75	8.33	13.10	15.81	13.84
	15	100	7.83	13.68	17.63	15.73

We present the data for B10, B20, and B30 fuel blends, along with all four compression ratios, under conditions of 75% and 100% loading. In all instances, the emissions of NOx decrease as the flow rate of water injection increases [73]. The NOx emissions exhibit a gradual rise until the water flow rate reaches 130.4 cc/mim. Then it remains nearly constant. The phenomenon may be attributed to the possibility that the reaction rate between H_2O and NOx emissions has reached its maximum level. Water was injected into the system at various flow rates, leading to a noticeable decrease in NOx emissions. The % NOx reduction is depicted in Table 4-30.

The Table 4-30 shows that the B10 blend results in an average reduction of NOx emissions of 7.38%, 12.04%, 17.07%, and 16.94% for flow rates of 38.7 cc/min, 82.7 cc/min, 130.4 cc/min, and 166.7 cc/min, respectively. The B20 blend yields average reductions of NOx emissions at rates of 38.7 cc/min, 82.7 cc/min, 130.4 cc/min, and 166.7 cc/min, resulting in reductions of 7.93%, 11.81%, 18.15%, and

17.63%, respectively. The average reduction in NOx emissions for the B30 blend at flow rates of 38.7 cc/min, 82.7 cc/min, 130 .4 cc/min, and 166.7 cc/min are 8.32%, 12.91%, 17.93%, and 17.69%, respectively. The NOx emission reductions are determined relative to the NOx emission measured when the water injection flow rate is zero for each specific blend and compression ratio. When nitrogen oxides dissolve in water and undergo decomposition, they give the formation of nitric acid (HNO_3) or nitrous acid (HNO_2), as stated in equation (ii) in Chapter 1.

Figure 4-24:Collection of Condensate from the exhaust pipe end for testing

We collected the condensate from the exhaust pipe's outlet as shown in Figure 4-24 and tested it in the lab to confirm the formation of HNO_2 and HNO_3. The test detected both HNO_2 and HNO_3. The test report has been attached in Appendix D.

4.4.2 Water Injection Effect on CO Emission

An effort was made to reduce the emission of nitrogen oxides by injecting water downstream of the engine. The water has a reaction with the CO emissions, resulting in the formation of CO_2 and H_2[50]. Equation (iii) in Chapter 1 designates this reaction as the water-gas shift reaction. Figure 4-25, Figure 4-26 and Figure 4-27 illustrate the effect of water injection on carbon monoxide emissions for four different CR (15, 16, 17, and 18) and for different fuel blends (B10, B20, and B30) under various loading conditions.

The reduction in CO emission has been observed. The % CO emission reduction rises as water injection flow rate increases.

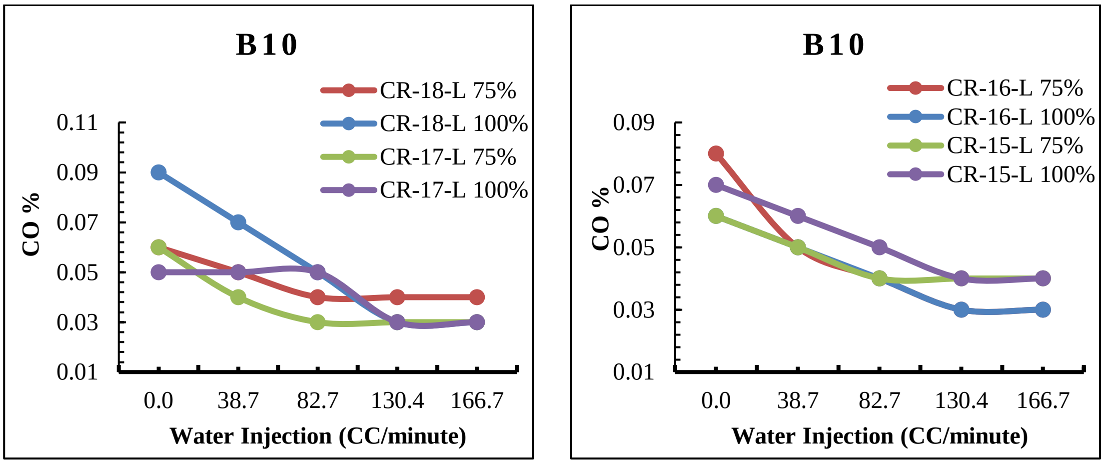


Figure 4-25:Effect of water injection on CO emission for B10 Blend

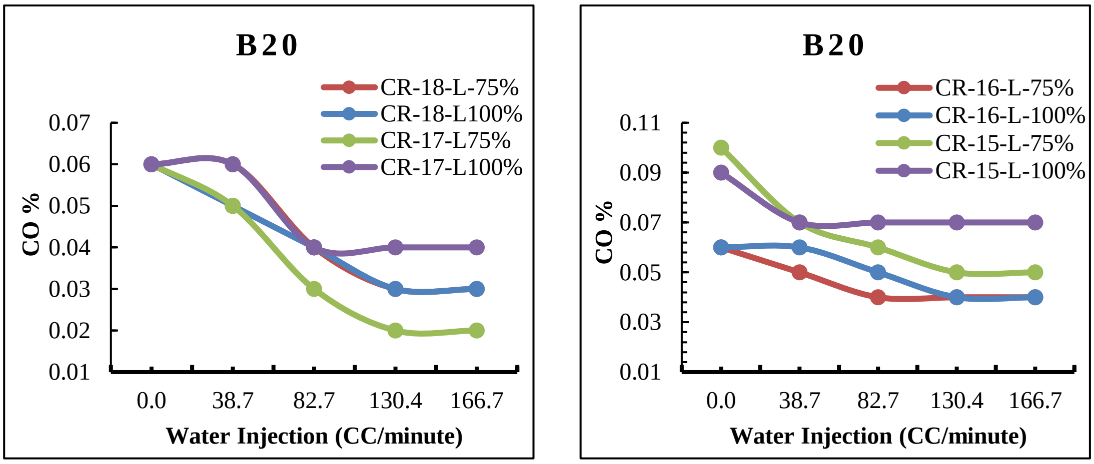


Figure 4-26:Effect of water injection on CO emission for B20 Blend

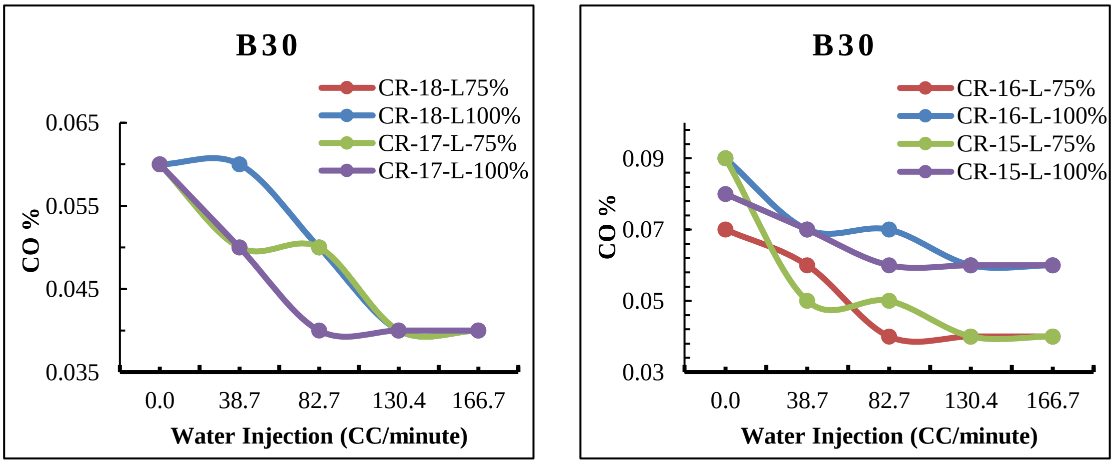


Figure 4-27:Effect of water injection on CO emission for B30 Blend

Table 4-31:CO emission reduction, water injection flow rate wise

Blend	CR	Load (%)	% Reduction in CO			
			Water injection flow rate (cc/min)			
			38.7	82.7	130.4	166.7
B10	18	75	16.67	33.33	33.33	33.33
	18	100	22.22	44.47	66.70	66.67
	17	75	33.33	50.52	50.50	50.00
	17	100	0	0	40	40.00
	16	75	37.50	50.00	62.50	62.50
	16	100	16.65	33.30	50	50.00
	15	75	16.80	32.90	33.32	33.33
	15	100	14.29	28.57	42.86	42.86
B20	18	75	0	33.33	50.00	50.00
	18	100	16.67	33.33	50.00	50.00
	17	75	16.67	50	66.67	66.67
	17	100	0	33.33	33.33	33.33
	16	75	16.67	33.33	33.33	33.33
	16	100	0	16.67	33.33	33.33
	15	75	30	40	50	50.00
	15	100	22.22	22.22	22.22	22.22
B30	18	75	25	50	50	50.00
	18	100	0	16.67	33.33	33.33
	17	75	16.67	163.67	33.33	33.33
	17	100	16.67	163.67	33.33	33.33
	16	75	14.29	42.86	42.86	42.86
	16	100	22.22	22.22	33.33	33.33
	15	75	44.44	44.44	55.56	55.56
	15	100	12.50	25	25	25.00

The Table 4-31 illustrates the average decrease in CO emissions for different flow rates of each fuel blend. The reductions in case of B10 are 19.68%, 34.13%, 47.40%, and 47.34% for flow rates of 38.7 cc/min, 82.7 cc/min, 130.4 cc/min, and 166.7 cc/min, respectively.

The average decrease in CO emissions for the B20 fuel blend at flow rates of 38.7 cc/min, 82.7 cc/min, 130.4 cc/min and 166.7 cc/min are 12.78%, 32.78%, 42.36%, and 42.12%, respectively. The average decrease in CO emissions for the B30 fuel blend at flow rates of 38.7 cc/min, 82.7 cc/min, 130.4 cc/min and 166.7 cc/min are 18.97%, 31.40%, 36.36%, and 38.34%, respectively.

The analysis reveals that the highest decrease in CO emissions is observed in case of B10 fuel blend, with CR 18 under 100% engine loading conditions, and the B20 fuel blend, with CR 17 under 75% engine loading conditions. For both the scenarios, the decrease is 66.67% when the flow rate is 130.4 cc/min. It has been noted that in all instances, the emission of CO decreases as the flow rate of water injection increases, reaching a maximum reduction at 130.4 cc/min. Additionally, the reduction remains constant at 166.7 cc/min. This phenomenon can possibly be ascribed to the maximum rates of reaction between CO and H_2O occurring at a flow rate of 130.4 cc/min.

4.4.3 Water Injection Effect on Smoke Emission

The smoke emission behavior with increasing water injection flow rate for B10, B20, and B30 fuel blends at different compression ratios and engine loading conditions is illustrated in Figure 4-28, Figure 4-29, and Figure 4-30

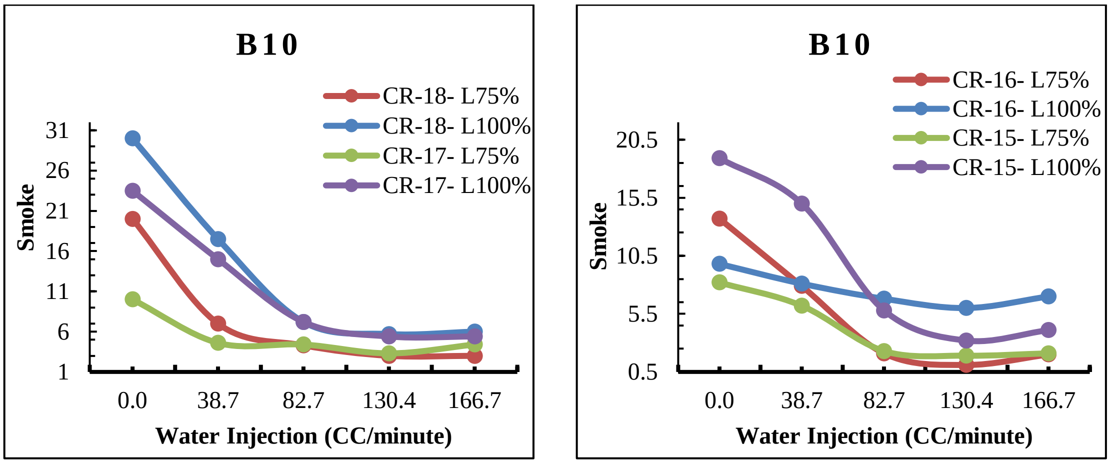


Figure 4-28: Effect of water injection on Smoke emission for B10 Blend

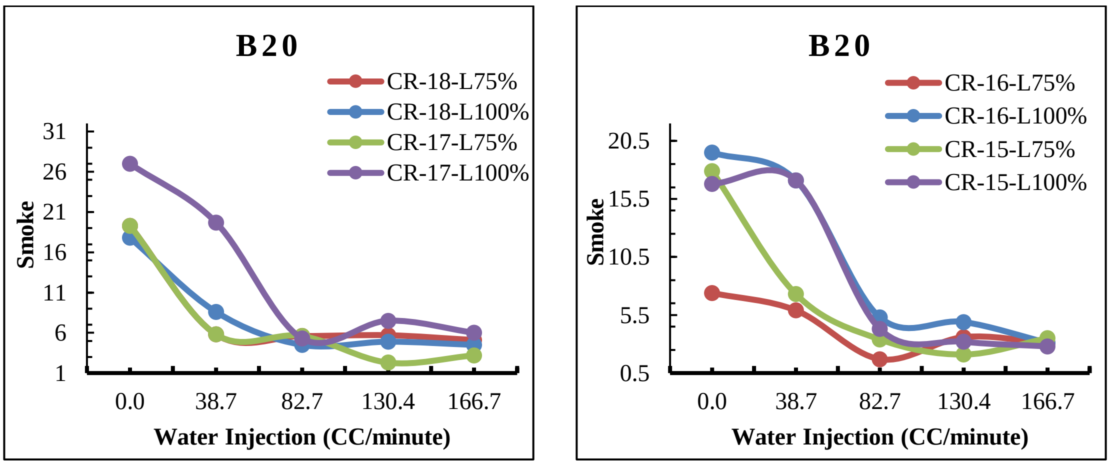
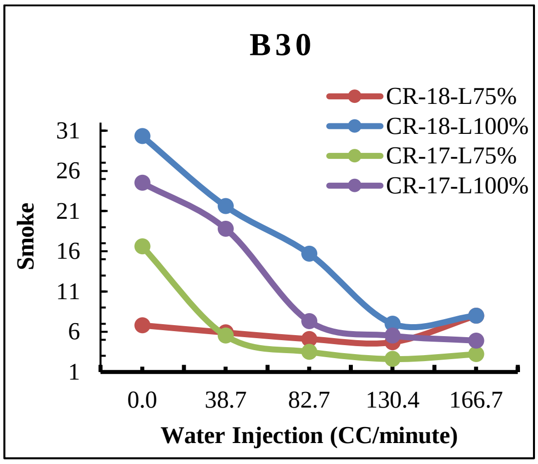


Figure 4-29:Effect of water injection on Smoke emission for B20 Blend

The findings indicate that there is a decrease in smoke emissions as the rate of water injection rises, with a maximum value of 82.7 cc/min observed in all instances. In addition, the smoke emission remained nearly constant for flow rates of 130.4 cc/min and 166.7 cc/min.



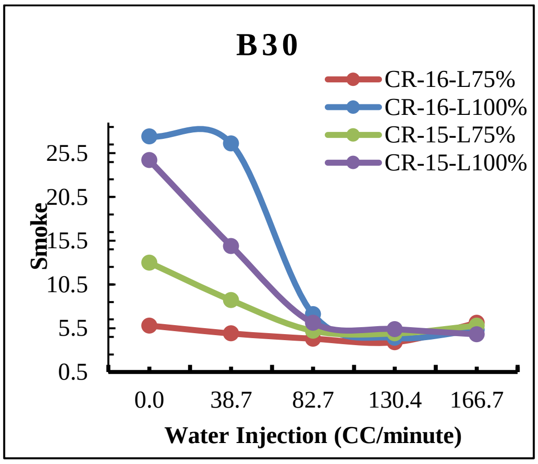


Figure 4-30:Effect of water injection on Smoke emission for B30 Blend

Table 4-32:Smoke emission reduction, water injection flow rate wise

Blend	CR	Load (%)	% Reduction in Smoke emission			
			Water injection flow rate (cc/min)			
			38.7	82.7	130.4	166.7
B10	18	75	65.00	78.50	85.00	85.00
	18	100	41.67	76.00	81.00	80.00
	17	75	54.00	56.00	67.00	56.00
	17	100	36.17	69.36	77.02	77.02
	16	75	42.34	84.67	91.97	85.40
	16	100	17.35	30.61	38.78	28.57
	15	75	24.39	71.95	76.83	74.39
	15	100	20.63	69.31	83.07	78.31
B20	18	75	69.95	70.98	70.47	73.58
	18	100	51.69	74.72	72.47	74.72
	17	75	69.95	70.98	88.08	83.42
	17	100	27.04	80.37	72.22	77.78
	16	75	20.27	77.03	51.35	58.11
	16	100	12.31	72.82	74.87	84.10
	15	75	59.22	81.01	88.27	80.45
	15	100	-1.79	74.40	80.95	83.33
B30	18	75	13.24	25.00	30.88	-17.65
	18	100	28.71	48.18	76.90	73.60
	17	75	66.87	78.92	0.06	80.72
	17	100	23.27	70.20	77.55	80.00
	16	75	15.52	25.86	32.76	-5.17
	16	100	2.92	74.09	83.94	80.66
	15	75	33.08	60.00	62.31	55.38
	15	100	39.68	75.30	78.14	80.57

The Table 4-32 shows the smoke emission reduction for B10, B20 and B30 fuel blends for all four CR. The average smoke reduction in case of B10 at flow rates of 38.7 cc/min, 82.7 cc/min, 130.4 cc/min and 166.7 cc/min are 37.69%, 67.05%, 75.08% and 70.59%. The average smoke reduction in case of B20 at flow rates of 38.7 cc/min, 82.7 cc/min, 130.4 cc/min and 166.7 cc/min are 38.58%, 75.29%, 74.84% and 76.94%. The average smoke reduction in case of B30 at flow rates of 38.7 cc/min, 82.7 cc/min, 130.4 cc/min and 166.7 cc/min are 27.91%, 57.19%, 58.17% and 55.51%

4.4.4 Water Injection Effect on HC Emission

The interaction between water particles and hydrocarbons results in the conversion of carbon into carbon monoxide and hydrogen, a process known as the water-carbon reaction.[124].

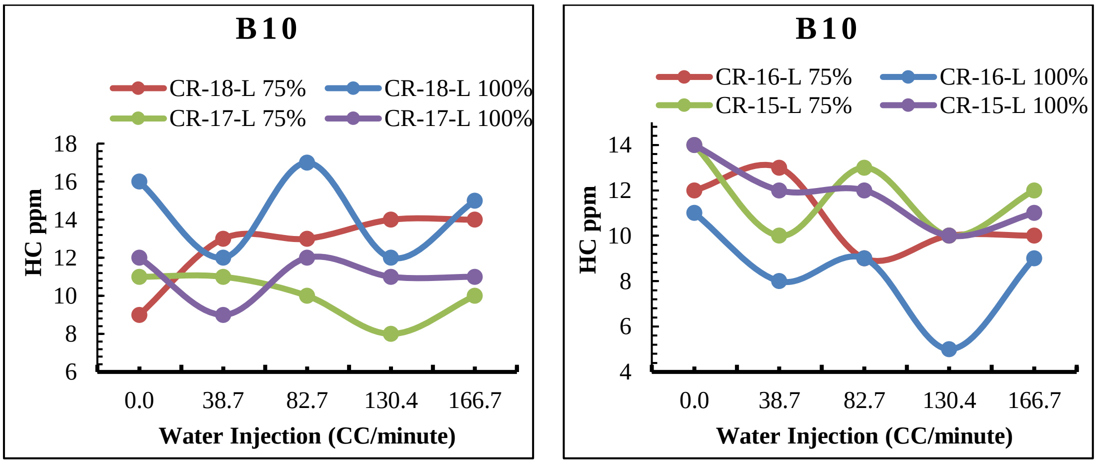


Figure 4-31:Effect of water injection on HC emission for B10 Blend

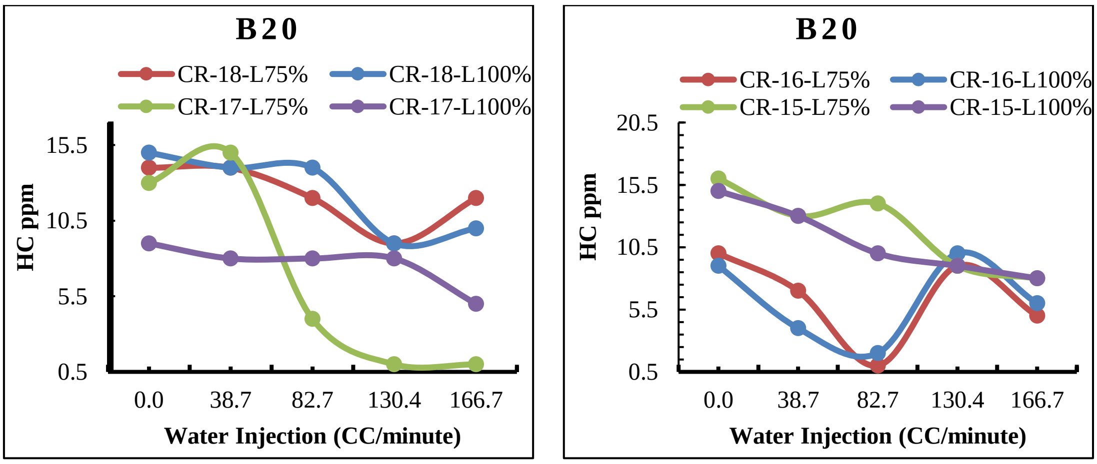


Figure 4-32:Effect of water injection on HC emission for B20 Blend

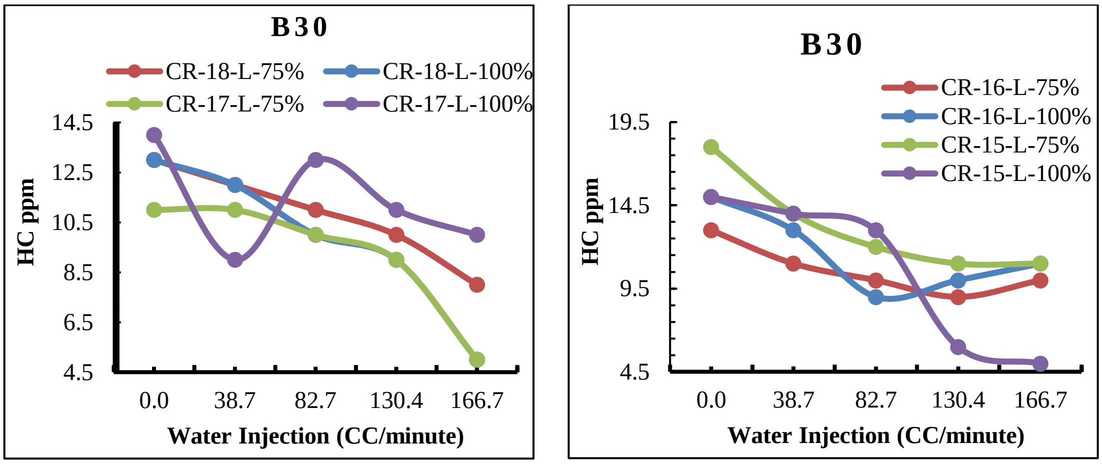


Figure 4-33:Effect of water injection on HC emission for B30 Blend

`In addition, the reaction between CO and water results in the formation of CO2, as previously described in Chapter 1 through the water-gas shift (WGS) reaction. The Figure 4-31, Figure 4-32, and Figure 4-33 depict the HC emission patterns for B10, B20, and B30 fuel blends in relation to the water injection flow rate, considering different compression ratios and engine loads. The findings indicate a negligible decrease in HC emissions.