Investigations of the Effect of Humid Air on NO_X & PM Emissions of a CNG Engine

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Project Objective

The goal of the investigation was to determine the feasibility of using a humid air system for reducing NOx emissions of CNG engines. Humid air system or fumigation has been an effective approach in reducing diesel NOx emissions. In this method, water vapor is injected in the intake air supplied to the engine cylinders. The process reduces the local temperature in the cylinder and raises the specific heat of the air-fuel mixture which also contributes to the elimination of the hot spots in the engine's cylinders. With decreased temperature, NOx reduction is achieved. With an optimized system, fumigation could reduce NOx emissions without significant increases in hydrocarbon emissions. Other benefits of this process include longer life of the engine components due to reduced cycle temperature and reductions in carbon deposits.

Problem Statement

About 29% of greenhouse gas (GHG) emissions in the U.S. is produced by the transportation sector. The major GHGs are carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4), and Hydrofluorocarbons (HFC). According to the intergovernmental panel on climate change (IPCC), if no additional measures are taken to reduce the GHG emissions, between years 2000 to 2030, the human source GHG emissions will increase 25% to 90% with CO_2 emissions growing between 40% to 110%. The corresponding global temperature rise will be between 2°F to 11.5°F by 2100 with 3-4 feet sea level rise. To limit the global warming to a range of 3.6°F(2°C) to 4.3°F(2.4°C), the GHG emissions must be reduced 50% to 85% below year 2000 by 2050. To meet this target, multi-disciplinary efforts must be undertaken with transportation playing a major role to limit GHG emissions.

Among strategies for reducing transportation GHG emissions are introduction of low carbon fuels, improving vehicle fuel economy and transportation system efficiency, and reducing carbon-intensive travel activities. The major GHG for CNG engines is NOx. The investigations have been focused on the effect of humid air intake on NOx and PM emissions of a CNG engine for substantial reduction in NOx emissions.

Research Methodology

The study was divided into two parts. In part one, numerical investigations of the effect of humid air at different levels of relative humidity on NO, CO, and CO_2 emissions of a non-premixed combustion of air and methane were performed. The study was performed using the existing combustion model of the Star CCM+ software by CD Adapco. The model solves the transport equation for the concentration of NO_X and is available for non- premixed and partially pre-mixed combustion. The outputs are fuel NO_X and thermal NO_X. In this study, the focus was on the thermal NO_X, since it consists a significant portion of the overall NO_X produced in CNG engines.

For experimental investigations, a General Motors inline 4 cylinders, naturally aspirated engine with a maximum rated horsepower (HP) of 50.8 for natural gas fuel was used. The engine was connected to a water-cycled dynamometer from Land & Sea which is equipped with automated data acquisition for engine performance tests. Figure 3 shows the experimental set-up. A special mixing tube was designed to add humidity to the intake air. A Rasco Vapour machine with distilled water was used to generate the added fog to the intake air. The humidity level of the intake air before and after adding humidity was measured with two TSI VelocCalc model 9565-P anemometers.

The experiments were performed at three levels of humidities and four engine rated horse powers (HP) of 5, 12.5, 25, and 37.5. The first level of humidity was the ambient humidity and the subsequent higher level of humidity was obtaind by increasing the percent humidity by 15% each time.

NOx emission was measured by a Horiba portable emission analyzer model 250. The exhaust PM measurements were involved using a dilution tunnel connected to a cyclone with Teflo filter.

Results

Tables 1 and 2 show results of both gaseous and PM emissions of the engine tests at various loading conditions. Cases 1-4 corresponds to the engine loadings of 5 HP, 12.5 HP, 25 HP, and 37.5 HP. The tests were performed at three different RHs of 30%, 45%, and 60%. The 30% RH corresponds to the ambient condition for the day that the test was performed. With addition of humidity, the NOx emission is reduced significantly for all cases studies. For case 1, at 60% RH, more than 60% reduction in NOx emission has been achieved and for case 4, which corresponds to the maximum loading condition, the reduction in NOx emission is at nearly 80%. The corresponding humidity-fuel mass ratio ranged from 0.64 to 0.82. Results indicate strong correlation between the humidity-fuel mass ratio and the % NOx reduction. It is expected that with a humidity-fuel mass ratio near 0.9, more than 90% NOx reduction could be achieved, especially at high loading conditions.

At low engine loads, the addition of the humidity results in significant increase in exhaust PM. For case 1, for 45% RH and 60% RH, the PM ratios ($^{PM_{45\%\ or\ 60\%}}/_{PM_{30\%}}$) are 5.6 and 8.3. These ratios for case 2 are 31.49 and 39.19 and for case 3 are 8.39 and 6.49 respectively. However at the highest loading condition (case 4), the ratios drop to around 2. Taking into account the loading HP, it indicate the PM weight per HP decreases significantly with increased HP.

Natural Gas Engine (50HP MAX)	Case 1			Case 2			Case 3			Case 4		
Power (hp)	4.9	4.8	4.9	12.6	12.7	12.8	26.5	25.1	25	37.4	36.5	37.7
Humidity Level (%)	0%	15%	30%	0%	15%	30%	0%	15%	30%	0%	15%	30%
Ambient Humidity (%)	31.5	49.3	65	25	43.5	68.2	27.8	45.2	64.7	24.7	40.3	63.2
Ambient Temperature (°F)	87	91.1	102.4	92.3	96.1	106.6	89.5	98.5	110.4	92.9	97.4	109.1
Air Flow Rate(cfm)	27.02	28.01	29.83	32.51	33.85	36.74	44.1	45.42	47.15	56.32	59.16	62.5
Fuel Consumption Rate (cfm)	2.22	2.30	2.34	2.74	2.82	2.95	3.65	3.61	3.69	4.54	4.47	4.48
<RAW>												
NOx (ppm)	134	108	47	259	115	64	688	203	60	984	238	199
SO2 (ppm)	42.4	34.9	26.8	42.6	22.3	21.1	51.7	18.1	11.6	41	10.2	17.5
CO (ppm)	3780	3055	3109	3690	1965	1880	4550	1745	1103	4467	1245	1785
CO2 (%)	10.02	8.27	5.66	10.23	5.12	4.34	10.03	3.75	2.37	9.07	2.32	3.98
O2 (%)	1.68	5.15	10.08	1.43	11.14	12.54	1.51	13.67	16.22	3.46	16.32	13.01
<Diluted>												
NOx (ppm)	19	19	13	43	38	22	110	94	45	190	142	84
SO2 (ppm)	11.6	11.8	13	12.1	12.4	13	13.2	13.1	12.7	13	12.4	12.7
CO (ppm)	690	673	685	712	712	704	843	817	771	917	803	778
CO2 (%)	1.8	1.81	1.72	1.84	1.81	1.78	1.8	1.81	1.67	1.74	1.59	1.7
O2 (%)	17.2	17.33	17.45	17.19	17.32	17.39	17.23	17.33	17.55	17.33	17.7	17.53
Dilution Ratio	5.70	4.57	3.29	5.56	2.83	2.44	5.57	2.07	1.42	5.21	1.46	2.34
mass_air (g/min)	889.43	915.16	955.03	1059.87	1096.01	1167.53	1445.05	1464.31	1488.35	1834.12	1911.04	1977.40
mass_humidity (g/min)	7.64	14.16	28.10	8.53	17.47	41.17	11.85	26.17	55.80	14.86	29.34	69.50
mass_fuel (g/min)	41.95	43.36	44.12	51.67	53.24	55.68	68.88	68.17	69.68	85.64	84.43	84.55
Humidity-Fuel Mass Ratio	1 : 5.49	1 : 3.06	1 : 1.57	1 : 6.06	1 : 3.05	1 : 1.35	1 : 5.81	1 : 2.60	1 : 1.25	1 : 5.76	1 : 2.88	1 : 1.22
Dilution tunnel flow rate (SCFH)	300	305	305	305	300	305	305	300	295	305	305	300
Dilution tunnel avg temp (°F)	93.33	97.00	101.00	95.67	106.67	108.00	99.33	111.33	112.33	70.33	111.67	113.00
Ratio of NOx to baseline	1.000	0.806	0.351	1.000	0.444	0.247	1.000	0.295	0.087	1.000	0.242	0.202
Ratio of CO to baseline	1.000	0.808	0.822	1.000	0.533	0.509	1.000	0.384	0.242	1.000	0.279	0.400

Table 1. Experimental Results for Gaseous Emissions

	PM weight (mg)				PM ratio				PM weight per hp (mg/Hp)			
Humidity Level (%)	Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4
0	0.764	0.194	0.583	1.287	1.00	1.00	1.00	1.00	0.156	0.015	0.022	0.034
15	4.278	6.106	4.890	2.678	5.60	31.49	8.39	2.08	0.891	0.481	0.195	0.073
30	6.210	7.598	3.783	2.907	8.13	39.19	6.49	2.26	1.267	0.594	0.151	0.077

Table 2. Experimental PM Emissions