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On-board measurement of particle numbers and their size distribution from a light-duty diesel vehicle: Influences of VSP and altitude

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ABSTRACT

In this study, the particle size-resolved distribution from a China-3 certificated light-duty diesel vehicle was measured by using a portable emission measurement system (PEMS). In order to examine the influences of vehicle specific power (VSP) and high-altitude operation, measurements were conducted at 8 constant speeds, which ranged from 10 to 80 km/hr at 10 km/hr intervals, and two different high altitudes, namely 2200 and 3200 m. The results demonstrated that the numbers of particles in all size ranges decreased significantly as VSP increased when the test vehicle was running at lower speeds (<20 km/hr), while at a moderate speed (between 30 and 60 km/hr), the particle number was statistically insensitive to increase VSP. Under high-speed cruising conditions, the numbers of ultrafine particles and $PM_{2.5}$ were insensitive to changes in VSP, but the numbers of nanoparticles and PM_{10} surged considerably. An increase in the operational altitude of the test vehicle resulted in increased particle number emissions at low and high driving speeds; however, particle numbers obtained at moderate speeds decreased as altitude rose. When the test vehicle was running at moderate speeds, particle numbers measured at the two altitudes were very close, except for comparatively higher number concentrations of nanoparticles measured at 2200 m.

Introduction

Approximately 26% of China's territory lies at altitudes higher than 1000 m. Currently, more than 15 million vehicles are operating within these high-altitude regions. It has been well understood that at high altitude, due to decreased atmospheric pressure and worsened intake motion, the in-cylinder combustion of diesel engines deteriorates (Shen et al., 1995) and causes remarkable power de-rating (Dennis, 1971) and efficiency loss (Wang et al., 2013a). Meanwhile, larger amounts of gaseous and particulate emissions are discharged by vehicles operating at high altitudes compared to those operating near sea level (Human et al., 1990). In order to address the nationwide problem of hazy weather, the sixth-stage emission standard for diesel

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engines of China is being drafted, and several retrofit programs for in-use diesel trucks, buses and construction machineries are also in progress. Apart from these counter-measures, high altitude operation of diesel vehicles, as an important source of extra particulate matter (PM) emissions, urgently requires detailed measurement and investigation.

In the absence of high-altitude emissions requirements, only the enhancement of engine dynamic performance was of concern in the studies done prior to the 1990s (Dennis, 1971 and Wu and McAulay, 1973). From the late 1980s to the mid-1990s, a series of experimental studies regarding high-altitude emission characteristics of diesel engines were performed by several American and Chinese facilities. By using a specifically-designed dilution tunnel, Human et al. (1990) compared the tailpipe emissions from two diesel engines operated at sea level and simulated high altitude. The results demonstrated that almost all the tailpipe emissions except for NOx increased with simulated altitude. In idle tests, the emission rate of PM measured at simulated high altitude was 3.6 times higher than the sea-level baseline.

Chernich et al. (1991) measured the smoke opacities of 84 in-use trucks running at both sea level and high altitude. On average, smoke opacities of trucks operating at an altitude of 5820 ft were 23 opacity points higher than those measured at 125 ft. Similar to Human's hardware settings, by using intake and exhaust throttles, Chaffin and Ullman (1994) mimicked the atmospheric pressures of Denver and Mexico City, and conducted emissions measurements on a DDC-60 diesel engine. Both PM and smoke emissions increased with simulated altitude in both steady- and transient-state tests. At the two simulated high altitudes, peak smoke opacities gauged in snap-smoke tests increased by about 60% and 80%, which were moderately larger than the margins reported by Human et al. (1990).

Graboski and McCormick (1996) examined the influences of fuel properties on the emissions from a high-altitude running DDC-60 diesel engine. Compared to sea-level operations, with the same diesel fuel, PM emissions measured at 5820-feet altitude basically increased by a half to two-thirds, which agreed well with Chaffin's report. An evident decrease in SOF contribution to overall PM was also noticed at high altitude, which suggested that increased PM emissions witnessed at high altitude should be attributed to an increase in residual carbon.

More recently, Benjumea et al. (2009) compared the combustion characteristics and engine dynamic performance of a diesel engine fueled with petroleum diesel and palm oil biodiesel working at 500 m and 2400 m. The results indicated that biodiesel fueling was able to shorten combustion duration and heighten in-cylinder pressure, therefore promoting the performance of high-altitude-operating engines.

By using a mobile engine dynamometer system, Wang et al. (2013a, 2013b and 2013c) and Yu et al. (2014) investigated the effects of increased altitude (up to 4560 m) and biodiesel use on the combustion and emission characteristics of a Euro-III certificated common-rail diesel engine. It was found that particle number persistently increased with altitude. When the engine was raised to 4500 m altitude, the particle number measured at idle increased by almost two orders of magnitude compared to that at sea level (Wang et al., 2013b). Using biodiesel to replace petroleum diesel could alleviate the diesel engine's dependence upon intake oxygen mass flow at high altitude (Wang et al., 2013c), which was found to be beneficial to lowering PM emissions (Yu et al., 2014). This advantage became even stronger as altitude increased. At 4560 m, the test engine emitted nearly 70% lower particle emissions with biodiesel fueling.

Similar conclusions were reported by Liu et al. (2014), who employed biodiesel-ethanol-diesel (BED) ternary fuel and biodiesel-diesel (BD) binary fuel to investigate the influences of altitude and fuel oxygen content on diesel engine performance and soot emission. The authors also noticed that engine-out soot emission was more sensitive to fuel oxygen content rather than increased altitude. Hence, better de-smoke performance could be attained with BED fueling at elevated altitude.

He et al. (2011) measured the emission characteristics of a modern diesel engine operating at simulated high altitudes. In bench tests, smoke opacities measured at 1200 r/min increased by more than six-fold when the engine was "raised" from sea level to 2000 m. With respect to particle number, it increased by approximately half an order of magnitude with an elevation of 1000 m altitude, since the engine tended to emit more nanoparticles and ultrafine particles.

All these findings highlight the risk of high-altitude PM emissions and the necessity to further conduct detailed investigations. With fewer variables, engine-level tests are convenient and reliable to help understand the combustion behaviors of high-altitude running diesel engines. However, it is very difficult to use engine test data to accurately calculate or predict real-world driving emissions because even a small change in the ground speed of test vehicle could translate to a large deviation of engine operating conditions (Yanowitz et al., 2002). Consequently, regarding environmental and health risks, it is preferable to conduct chassis-level measurements, either in the laboratory or the field.

Due to the high cost and complexity of on-board emission measurement, reports of high-altitude vehicle emission tests are less commonly seen than engine-based ones. Bishop et al. (2001) collected 5772 sets of on-road heavy-duty truck emissions by setting up remote-sensing equipment in five U.S. cities. A statistical increase in all criteria for gaseous emissions with the increase of altitude was concluded, but unfortunately, non-contact emission measurement technology was unable to reliably gauge smoke opacity at that time, so no result on smoke was mentioned. Yin et al. (2013) and Wang et al. (2013d) measured the criteria for gaseous and particle emissions from a Euro-III certificated commercial van at multiple altitudes. Both CO and HC emissions increased with altitude and decreased with vehicle speed. PM emissions also increased with altitude, but showed a general uptrend when the test vehicle accelerated. The size distribution of tailpipe particles given by Yin et al. (2013) revealed that diesel vehicles operating at high altitude discharged more small particles and had higher volumetric number concentrations. This differed from He's results that nanoparticles were found to be the prime contributors to particle number, but not ultrafine particles. Unfortunately, the authors only gave the volumetric number concentrations of total particle number (PN), and with no access to engine exhaust flow rates, it is impossible to project real-world PN emissions.

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