Water in Diesel Combustion

W. Addy Majewski

Abstract: Addition of water to the diesel process decreases combustion temperatures and lowers NOx emissions. The most common methods of introducing water are direct injection into the cylinder, a process commercialized in certain marine and stationary diesel engines, and water-in-fuel emulsions. Emulsified fuels, due to increased mixing in the diesel diffusion flame, can be also effective in simultaneous reduction of PM and NOx emissions.

1. Addition of Water to Diesel Process

1.1 Methods of Water Addition

Addition of water into the diesel combustion process is a known method to reduce NOx and, in some implementations, simultaneously reduce NOx and PM emissions. The very notion of introducing water into the cylinder of the diesel engine may sound controversial. After all, engineers have been taking great care to accomplish the exact opposite and protect the combustion chamber from water contamination, be it from the fuel or from water condensation in intake air coolers. The controversy around water addition is founded on the observation that water droplets impinging on the cylinder walls can immediately destroy the lubrication oil film. This danger however, although very real, is posed exclusively by liquid water. Once water is evaporated, it can no longer affect the lube oil film [Holtbecker 1998]. Thus, water addition methods which ensure that water droplets cannot contact the cylinder liner surface may be considered harmless. Further concerns have been raised that increased concentrations of water vapor in engine cylinder may result in condensation of water and/or sulfuric acid leading to corrosion problems. Apparently, these suspicions are not justified either, as the dew point of sulfuric acid at very high water:fuel ratio of 1:1 is increased by only up to 15°C [Vollenweider 1995]. Considering the temperatures in diesel combustion, condensation in the combustion chamber is not possible at any time.

In general, water can be introduced into the diesel combustion process using one of the following methods:

- Emulsified fuel
- In-cylinder water injection
- Water injection into the intake air

These methods are shown schematically in Figure 1.

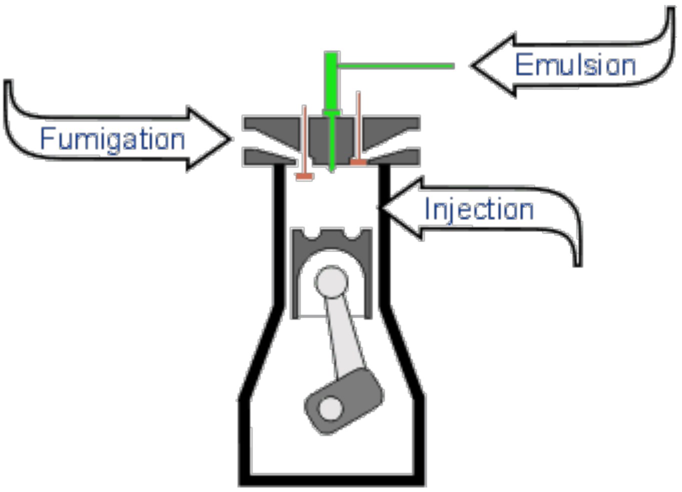

Figure 1. Water Addition Methods

Emulsion is a system consisting of two immiscible liquids, one of which is finely dispersed in the other. In all water/diesel fuel emulsions of practical importance water is dispersed in the form of fine droplets in the continuous diesel fuel phase. This type of emulsion, schematically shown in Figure 2, is often referred to as “water-in-fuel” emulsion. In the opposite configuration, with fuel dispersed in the continuous water phase, water would be much more likely to contact the cylinder liner surface and other metal parts, leading to corrosion and engine problems.

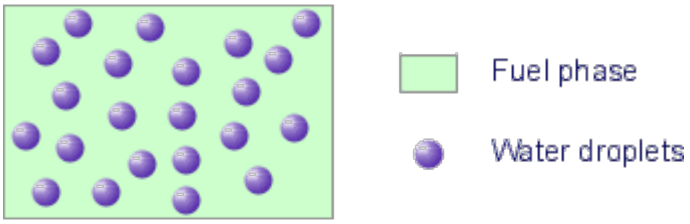

Figure 2. Water-in-Fuel Emulsion

In practice, running an engine on water-fuel emulsion makes it possible to reduce NOx by up to about 50% with the required water quantity being about one percent for each percentage point of NOx reduction [Holtbecker 1998]. The limiting factor for water emulsions is the delivery capacity of the injection system. If emulsions are to be used without engine modifications (e.g., to substitute regular fuel in existing engines), the maximum quantity of water and the degree of NOx reduction are both limited to some 10-20%. Even then, the engine may not be able to reach its rated power, running in effect at a slightly derated condition.

Emulsions are distinguished among other methods of water addition by the fact that water, being incorporated into the fuel spray droplets themselves, is introduced directly into the combustion flame area where emissions are formed. In addition to the NOx benefit, which in all methods is attributed primarily to the lowering of combustion temperature by water, emulsions result in enhanced fuel spray atomization and mixing. Enhanced mixing which extends throughout the diffusion flame can bring quite impressive reductions of PM emissions. As a result, water-fuel emulsions are one of the rare diesel emission control strategies that can simultaneously reduce NOx and particulate emissions without or with only a small fuel economy penalty. Reduction of PM emissions by emulsions has not yet been as thoroughly researched as NOx reduction. Nevertheless, as will be discussed later, the achievable effectiveness of PM reduction appears to be more than twice the level of NOx reduction.

In-cylinder injection of water requires a separate, fully independent injection system, preferably under electronic control. This method offers the capability to inject very large quantities of water without the need to derate the engine. This system also allows to switch the water injection on and off, as may be needed, without affecting engine reliability. Direct water injection needs to be carefully optimized with respect to injection timing, water consumption, emissions, and other parameters. This flexibility in optimizing parameters allows to achieve NOx reductions similar to those seen in emulsion systems, despite the fact that water is not introduced directly into the diesel flame area as an integral part of the spray. However, PM emission reductions, if any, do not match those with emulsified fuels. The complex development work required for water injection systems in different engine types makes this approach suited for OEM rather than for retrofit applications.

Fumigation, meaning the introduction of water into the intake air, is the most simple method of water addition. This method offers very little control over the injection parameters such as timing or spatial coordinates. For this reason, observed NOx reductions tend to be lower than those with emulsions or direct injection. Fumigation typically reduces NOx emissions by 10% for each 20% water addition to the fuel [Holtbecker 1998].

If the fumigated water does not completely evaporate in the intake air, it will impinge on the cylinder walls causing disintegration of the lube oil film and engine damage. A safer approach is to fumigate water vapor rather than liquid. Water vapor may be generated using waste heat from the engine, such as from the exhaust gas and/or from the compressed charge air. Another possibility is to use steam, which may be available in certain stationary engine applications.

Regardless of the method of water addition, consideration must be given to the logistics of providing the water supply. The use of emulsifying agents allows for preparing emulsions that can remain stable for a number of days or even weeks. In this case, vehicles may be simply fueled with emulsion in place of regular fuel. Such application of emulsions is obviously limited to vehicle fleets that are centrally fueled from one facility where the emulsion would be prepared. Other water addition methods would require that water tanks and handling systems are installed on the vehicle. The obvious drawback of such systems is the large quantity of water that is needed for NOx reduction, which would require large tanks and frequent replenishment. This is likely the main reason why water addition technologies attract more attention in stationary and marine applications, where supplying large quantities of water is less problematic. However, most systems for ocean going ships would work on fresh water only, thus requiring additional fresh water generation equipment.

References

Holtbecker, R., Geist, M., 1998. “Exhaust emissions reduction technology for Sulzer marine diesel engines: General aspects”, Wärtsilä NSD Switzerland Ltd., Winterthur, Switzerland, July 1998

Vollenweider, J., Geist, M., Schaub, M., 1995. “Residual fuels in emission-controlled diesel engines: Background, developments and operational results”, Proceedings of the 1995 CIMAC Congress, Interlaken, Switzerland

###