Characterization of Nozzle Tip Temperature of Diesel Injector in a Dual Fuel Engine

Fabio E. Czarneski*[1,2], Stephan H. Och[2], Luís M. Moura[2]

[1]Robert Bosch Ltda, Diesel Systems, DS/EDF-LA, Curitiba, Brazil
[2]Pontifical Catholic University of Paraná – PUCPR, Curitiba, Brazil

Abstract

In this experimental study, carried out in a dual fuel Diesel-CNG engine, a general characterization of the diesel injector nozzle tip temperature (NTT) is presented. Measurements were done in a three phase asynchronous dynamometer with objective of quantification of the influences of diesel substitution rate, injection phasing, injection pressure and air-fuel ratio over the nozzle tip temperature. High NTT values increase the formation rate of coking on nozzle holes. The first experimental results showed that temperature increases with increasing on substitution rate, with injection timing advancing and with reduction on air fuel ratio. Rail pressure at 60% of substitution rate has also significant influence on NTT values. These results suggest that the referred engine parameters play a important role on NTT control and have to be considered, not only at the end of calibration, but also during engine calibration work to obtain a good trade-off between NTT and other engine limitations.

Introduction

Natural gas is an attractive alternative fuel due its clean burn characteristics and abundance in some regions of the globe [1]. Aiming to obtain benefits over these two characteristics, the usage of compressed natural gas(CNG) in commercial vehicles is raising as a satisfactory alternative, since it brings reduction on operational costs and lower environmental impact [2,3].

The dual fuel technology is one alternative on this context, since it uses simultaneously diesel and CNG as fuel. In this technique, CNG is the primary fuel and diesel acts as a pilot to ignite the air-fuel mixture.

Dual fuel engines are considered a good choice on replacement of diesel engines of commercial vehicles fleets, as it offers the advantage of reduced emissions of nitrogen oxides, particulate matter, and carbon dioxide while retaining the high efficiency of the conventional diesel engines [4, 5].

The dual fuel engine has distinct operation characteristics for each load and speed condition. In low idle and light loads, it runs with 100% diesel; and with moderate and high loads the diesel is replaced by CNG in different rates, typically going up to 80% in the best cases [6].

In regard overall thermal efficiency, there is no significant difference while operating in dual fuel mode. Although the thermal efficiency values at low power are lower than pure diesel operation, at high power outputs the dual fuel operation produces similar or higher thermal efficiency [7].

One of the main targets during the development and calibration of the dual fuel engine, is to use the largest possible amount of natural gas in a wider operation area, and get proportional reduction on diesel amount injected at combustion chamber as pilot for the mixture ignition, aiming maximize the benefits of CNG burning on overall vehicle operation. As the cooling of nozzle injector, especially the tip area, is done mainly by the flow of diesel which is injected, by reducing the amount of diesel that pass through the nozzle, cooling is also decreased, which lead to increase on nozzle tip temperature (NTT) values.

Additionally, high NTT values increase the formation rate of injector deposits. This phenomenon is also known as coking [2, 8].

In other hand, as the specific heat capacity ratio of CNG is higher than for air, the dual fuel operation should lead to an overall increase in the heat capacity for the in-cylinder mixture resulting in a reduced average temperature at the end of compression stroke and an overall lower combustion temperature. It was reported by Imran [7] that peaks of rate of energy release in dual fuel operation is slight lower when compared to diesel operation, fact that should contribute to reduce heat incidence at nozzle tip and therefore reducing the NTT values, but the experimental investigation done by Lounici [9] contradicts these results and states that the in-cylinder pressure in dual fuel mode and at high loads becomes higher than the pure diesel engine, due an improvement on gaseous fuel combustion. These opposite results found at literature reveal that the combustion at dual fuel engine is not yet completely understood and the correct trend for combustion peak temperature is highly dependent on engine parameters and has to be carefully mapped in each different engine application.

These unique characteristics of dual fuel engine in regard nozzle cooling is a novelty and indicates that NTT is emerging as an important limit for these engines and has not be neglected, but carefully tracked during overall calibration work.

To carry out the NTT measurement, a K-type thermocouple was installed into a common rail injector as close as possible from nozzle tip, with no interference on the injector function.

* Corresponding author: fabio.czarneski@br.bosch.com
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NTT context and main influences

In this section a brief review of heat transfer mechanism at nozzle tip is presented, the parameters identified as relevant for NTT are listed and a simple model for heat transfer is described.

Although instantaneous temperature of the work fluid varies widely during the thermodynamic engine cycle, the assumption that the heat-transfer process at diesel nozzle during the engine steady-state operation is *quasi steady* [10] is sufficiently accurate for the purpose of this work.

The amount of heat to be dissipated by the nozzle is dependant of the combustion characteristics and, therefore, the engine calibration parameters [2, 7]. Calibration parameters directly identified [2] as relevant for NTT values are the substitution rate (SR) of diesel by natural gas, considering the energy content in each fuel; the relative air/fuel ratio of mixture (λ); the diesel injection phasing, which is controlled through begin of diesel injection (θ_0); the diesel injection pressure (P_{rail}) at common rail system; and the exhaust gas recirculation (EGR) rate. The boundary conditions identified as relevant for NTT are the engine coolant and the inlet air temperatures.

The indirect combustion characteristics that may influence on NTT values were also identified and are listed as follow: early injection timing increases the peak flame temperature [11] and therefore will increase the heat incidence at nozzle and can lead to higher NTT; higher SR reduces the peak combustion pressure [12, 13] and can reduce the NTT since the heat incidence at nozzle tip is smaller.

In order to get a better understand of the basic mechanism that manage the heat transfer process over the diesel nozzle, a simple model is proposed by Königsson [2] and can be seen at Figure 1.

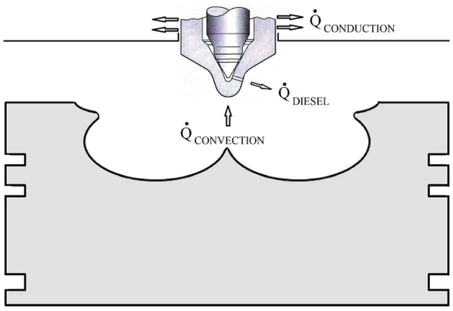

Figure 1 - Global heat transfer process at diesel nozzle

The heat incident at cylinder walls and at diesel injector nozzle comes from the hot gases resultant from combustion process and is dissipated by the nozzle. The heat dissipation at nozzle can be separated in two parts: one that comes to the cylinder head and to the cooling fluid and other that is extracted by the diesel fuel that passes through the injector.

The equilibrium condition is dependent on engine speed and load. In a steady state condition, equilibrium of these three parts is reached, according Eq. 1 [2].

$$\dot{Q}_{CONVECTION} - \dot{Q}_{DIESEL} - \dot{Q}_{CONDUCTION} = 0 \qquad \text{Eq. 1}$$

In fact, heat transfer process at nozzle takes place in 3D and is much more complex that this simple model can explain, but from engine calibration *vies* and for the purpose of this work, it is acceptable and shall suffice to start the discussions about NTT behavior.

Equipment and Method

In this section the experimental setup at dynamometer is described, the method to record NTT and its accuracy is presented and the main engine limitations that have to be observed during data acquisition are listed.

Table 1 - WP10 engine specification

Total Displacement volume [dm³]	9,73
Number of cylinders [-]	6
Cylinder bore [mm]	126
Piston stroke [mm]	130
Compression ratio [-]	17:1
Maximum torque [Nm@n]	1650@1300...1400
Maximum Power [kW@n]	257@1900
Emission level (diesel engine)	EURO-IV
Valves No. (inlet/outlet)	2/2

The experimental investigation was carried-out in an AVL three phase asynchronous dynamometer, using a 10 liters 6-cylinder compression ignition engine, with direct diesel injection, modified to operate in dual fuel mode. The engine is a Weichai WP-10 model. The Figure 2 shows a basic layout of this engine.

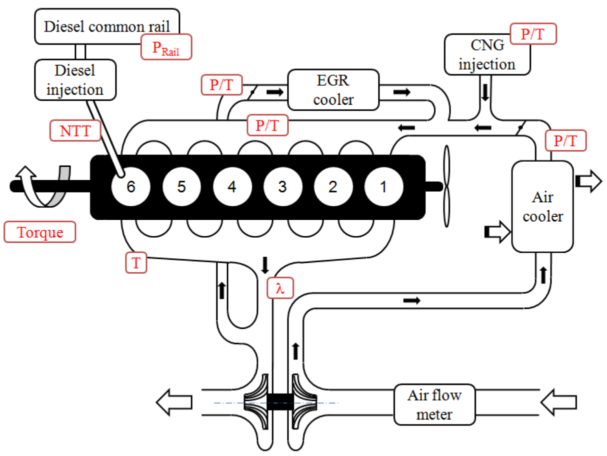

Figure 2 – WP10 Engine layout and main measurement points

CNG is supplied to the test bench from bottles at 200 bar and the pressure regulator valve reduces the line pressure to around 7 bar, injection is done in the inlet manifold using a set of injectors electronically controlled. CNG injection amount is corrected by the instantaneous manifold pressure and temperature through a combined sensor at manifold upstream gas injection. Gaseous fuel is then inducted at engine air inlet manifold after compressor and flow to the plenum. The resultant mixture of air and CNG that reaches the plenum is considered in this experimental investigation as a homogeneous mixture.

Air mass flow is measured through a hot film anemometer able to measure from 80 to 2400 kg/h with less than 1% of measurement uncertainty.

Air flow control is done electronically through measurement of relative air/fuel ratio at exhaust tube and using a throttle valve at inlet air manifold, throttling the air excess and allowing a very accurate λ. Its definition is shown on Eq. 2 where A/F is the air/fuel ratio.

$$\lambda = \frac{(A/F)_{Stoichiometric}}{(A/F)_{Actual}} \qquad \text{Eq. 2}$$

The diesel pilot injection is done by the standard equipment of the diesel engine, a common rail system of 1800 bar.

The SR is defined in Eq. 3 and is weighted by the specific heat value (LHV) of each fuel.

$$SR = \frac{\dot{m}_{CNG} LHV_{CNG}}{\dot{m}_{CNG} LHV_{CNG} + \dot{m}_{DIESEL} LHV_{DIESEL}} \qquad \text{Eq. 3}$$

On this work, the LHV is 48750 kJ/kg [14] and 42500 kJ/kg [15] for the CNG and diesel fuel respectively. Diesel injection phasing is controlled by an electronic control unit (ECU) through θ_0 parameter. By definition, the positive values of θ_0 are the values before top dead center (BTDC) and negative values are the values after top dead center (ATDC)

The diesel injection pressure (P_{rail}) is also a parameter controlled by the ECU and can be calibrated at maximum pressure of 1800 bar in this system.

Auxiliary systems at dynamometer room are available to control the engine boundary conditions: At the intake air manifold an air-water heat exchanger cool down the air temperature at required value by controlling the water flow; and at engine coolant circuit a shell-and-tube heat exchanger is being used and by controlling the water flow allows the control of engine coolant fluid temperature at engine circuit.

All engine management is done by two ECUs with specific dual fuel software able to control both fuel systems simultaneously. The communication between the ECUs is done via controller area network (CAN) bus.

The calibration parameters are sweep and the NTT values recorded, considering the engine limitations as maximum combustion pressure and maximum exhaust temperature. Additionally, dual fuel engine is susceptible to knock, an abnormal combustion that can cause major engine damage when takes place as severe and even if not severe, can produce a characteristic noise [10], that has to be avoided and is monitored continuously for this work.

Temperature at nozzle tip is being measured using a thermocouple k-type, 0.5mm diameter placed at the shaft of diesel injector nozzle, close from the tip area, as shown on Figure 3 and Figure 4.

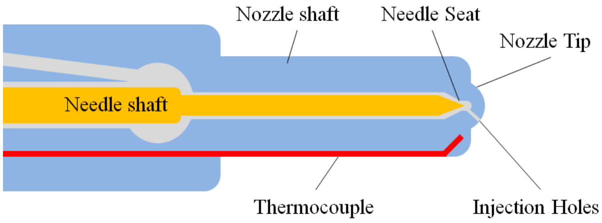

Figure 3– Scheme of diesel injector nozzle instrumented with thermocouple reaching the tip area.

Evaluation of uncertainties of all measurement is crucially important. Experience has shown that no measurement, however carefully made, can be completely free of uncertainties [16]. In a measurement system, the whole measurement chain has to be considered and the propagation of uncertainty evaluated.

The NTT measurement system is composed by the thermocouple K-type, an analogic/digital (A/D) converter and the data recorder. Uncertainties at measured NTT values based on manufacturer’s data at the usual range from 500 to 700K are from 6.1 to 7.7K, respectively.

Due to constructive reasons the measured NTT doesn’t mean the real tip temperature but the internal average temperature of the end of the nozzle shaft in a *quasi steady* condition. By convenience, this measured temperature values at this way are assumed as nozzle tip temperature in this work.

Figure 4 - Common rail injector instrumented for NTT measurement

Combustion pressure is being measured using a piezoelectric sensor with 19 pC/bar of sensibility, placed into the cylinder head in front of the combustion flames, as shown in the Figure 5.

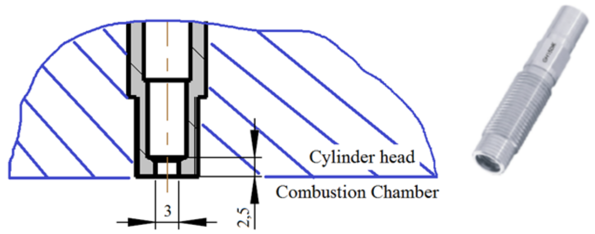

Figure 5 – Piezoelectric pressure sensor and installation details at engine cylinder head

Average exhaust temperature of each individual cylinder is being measured with k-type thermocouples with diameter of 3 mm placed in the exhaust gas runner. Accuracy of exhaust temperature measurement is around 12°C at 1000K.

To handle with possible knock phenomena, a knock monitoring is being used. The knock tendency is monitored through a filtered and integrated signal of two vibration sensors, able to detect early the knock events. ECU reacts accordingly to prevent damages at engine.

Table 2 - Baseline settings

Engine speed [rpm]	1300
Torque [N.m]	1104
Engine coolant temperature [°C]	80
Inlet air temperature [°C]	40
SR [%]	60
λ [-]	1.5
Diesel rail pressure [bar]	1200
Injection phasing [θ BTDC]	0

The baseline settings for this work are listed in the Table 2 and were used for all data acquisition, except if explicit informed.

Table 3 - Sweep parameters range

SR [%]	0…95
Injection timing [θ_0 BTDC]	+10…-7
λ [-]	1.2…1.8
Diesel rail pressure [bar]	500…1800

During each individual parameter sweep, the remaining baseline parameters were kept constant. Sweep range is shown on Table 3.

Results and Discussion

In this section the results of a quick sweep of the main engine parameters over its expected calibration range and the influence on NTT value is presented. The overall trend is also identified.

The tested parameters were the SR, P_{rail}, θ_0, and λ. The already acquired data are enough only to indicate the general tendency and weight the influence of the tested parameters over NTT. A more deep investigation is foreseen for the next months for other relevant parameters and boundary conditions, as identified at item Introduction, with smaller measurement steps and wider range, aiming a more accurate identification of the influence of the relevant parameter on NTT values.

The substitution rate influence on NTT is shown on Figure 6. It is clear that SR have a big influence on NTT, mainly at high substitution rates, and reinforces the assumption that a great amount of heat is removed by the diesel fuel that passes through the injection nozzle and is injected at combustion chamber.

It is important to notice that the engine load output is constant during change on SR; it means that heat incidence at nozzle remains constant while nozzle cooling is being reduced by reducing the diesel flow.

Diesel injection pressure variation is shown on Figure 7 and the NTT tendency is to increase NTT by increasing the pressure in a linear way. This behavior may be related to the reduction on injection time at high rail pressures. The less injection time, the less heat transfer time. Another possible explanation for this phenomenon is that at higher injection pressure, the heat produced by shear forces over the diesel are higher, with more heat generation and higher diesel temperatures, reducing the global heat transfer from nozzle to diesel fuel.

Figure 8 shows that engine phasing, with positive values before top dead center (TDC), and negative values after TDC, have also a non-negligible influence on NTT values. It is noticeable that the early represents the pilot diesel injection, and the higher represents the NTT values.

The λ is also an important parameter on NTT values, as shown on Figure 9. By reducing the λ value, there is an increase on NTT values.

It is important to notice that for all the results shown on Figure 7, Figure 8 and Figure 9, the injected diesel amount remains constant at 62 mg per injection, therefore there is a constant nozzle cooling by diesel flow.

Conclusions

The present work aims to investigate the tendencies of temperature at nozzle tip, with engine parameters variation and weight the contribution of each one in NTT values. Experimental investigation was started in a full 6 cylinder diesel engine and main tendencies were pointed-out. Investigation work was not concluded yet.

The main findings at this initial study were:

1. The most effective parameter to control NTT is the SR, but is also the parameter that has to be maximized, in order to make the dual fuel engine economically viable. Thus, the SR has to be the last option on NTT control strategy.

2. Other investigated parameters are significant on NTT control and effectiveness order are injection phasing, λ and injection pressure.
3. The identification of trends for NTT values can be useful for future orientation on general calibration tasks, if instrumented injector is not available at the engine or for general nozzle tip temperature prediction for dual fuel engines.

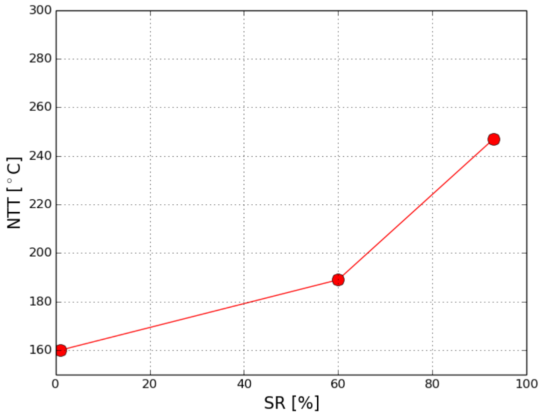

Figure 6 - NTT vs. substitution rate

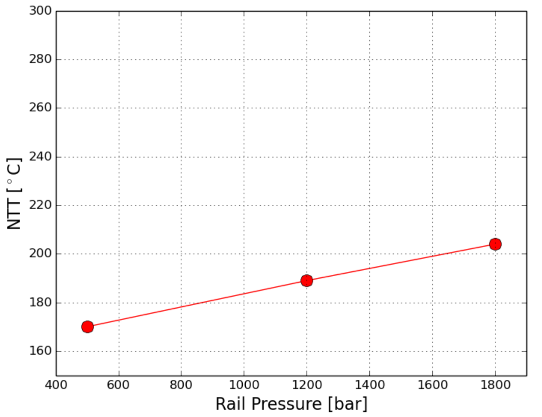

Figure 7 - NTT vs. diesel rail pressure

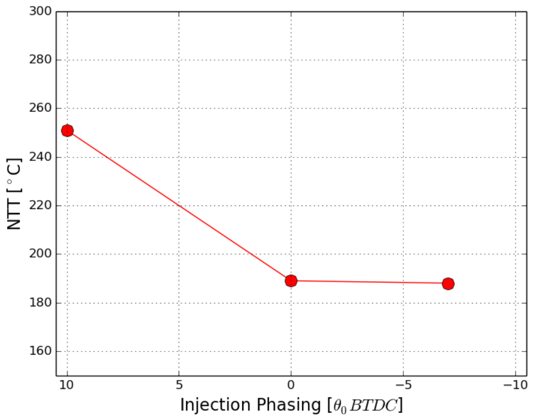

Figure 8 - NTT vs. diesel injection phasing

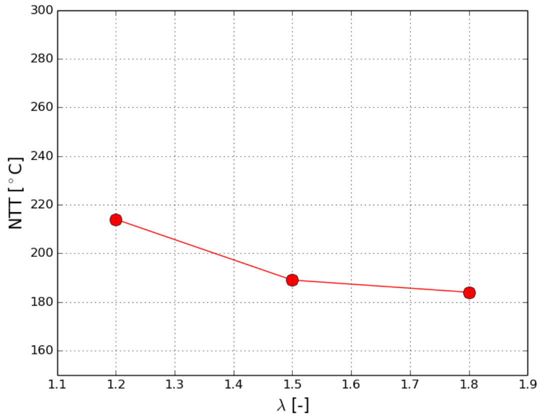

Figure 9 - NTT vs. relative air/fuel ratio

These results suggest that the referred engine parameters play a important role on NTT control and have to be considered, not only at the end of calibration, but also during engine calibration work to obtain a good trade-off between NTT and other engine limitations.

A more deep investigation is foreseen for the next months with smaller measurement steps and wider range, aiming the confirmation of the calibration characteristics, a more accurate identification of temperature trends and quantification of impact of each variable in the NTT values.

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