

Diesel Exhaust Fluid (DEF) Supply System Modelling for Control and Diagnosis Applications

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ABSTRACT

The Selective Catalytic Reduction (SCR) system installed on the exhaust line is currently widely used on Diesel heavy-duty trucks and it is considered a promising technique for light and medium duty trucks, large passenger cars and off-highway vehicles, to fulfill future emission legislation. Some vehicles of these last categories, equipped with SCR, have been already put on the market, not only in the US, where the emission legislation on Diesel vehicles is more restrictive, but also in Europe, demonstrating to be already compliant with the upcoming Euro 6. Moreover, new and more stringent emission regulations and homologation cycles are being proposed all over the world, with a consequent rapidly increasing interest for this technology. As a matter of fact, a physical model of the Diesel Exhaust Fluid (DEF) supply system is very useful, not only during the product development phase, but also for the implementation of the on-board real-time controller. This paper describes the activity performed to develop and characterize a 0-D model of the DEF supply system, oriented to model-based control and to the simulation of the system response to fault injections, finalized to diagnosis validation.

CITATION: Stola, F., De Cesare, M., Lacchini, L., Cavina, N. et al., "Diesel Exhaust Fluid (DEF) Supply System Modelling for Control and Diagnosis Applications," *SAE Int. J. Engines* 8(1):2015, doi:10.4271/2015-26-0090.

INTRODUCTION

The progressive tightening of the limits defined by antipollution regulations in many countries, led the automotive industry to develop control and pollutants abatement technologies increasingly sophisticated and effective. To achieve limits like Euro 6 or Tier 2 and LEVII in a Diesel engine, it is no longer sufficient to implement control actions within the combustion chamber, such as multiple injections, Exhaust Gas Recirculation (EGR), fluid dynamics optimization, turbocharging, etc., but it has become necessary to adopt exhaust emissions after-treatment systems. A significant reduction of nitrogen oxides concentration in the exhaust gas can be achieved through the Selective Catalytic Reduction (SCR), which essentially operates by reducing the NO_x to nitrogen (N_2) and water vapour (H_2O). The basic operating principle of the SCR system in question consists in the addition of ammonia as a reducing reagent, inside an appropriate catalytic reactor.

To this day the problem of direct use of ammonia, a substance considered toxic, as a reagent has been overcome through the storage and transport of the reductant in a more secure form, represented by a water-based solution (32.5%) of urea ($\text{CO}(\text{NH}_2)_2$), called DEF. This compound has the characteristic of not being classified as hazardous to humans and the environment, and not being flammable; therefore it

can be used with fewer precautions than pure ammonia. It is typically stored on board the vehicle inside dedicated tanks, and injected into the gas flow upstream of the converter. DEF then transforms into ammonia, thanks to the high temperatures of the exhaust gas, and to the action of the catalytic converter. The ammonia thus produced reacts with nitrogen oxides reducing them to nitrogen (N_2) and water vapour (H_2O). Activation reactions are facilitated by the presence of the catalytic converter that lowers the activation energy allowing to achieve high reduction efficiencies in a rather wide temperature range (170-500 °C). The SCR system performance strongly depends on the correct injection of reagent amount, which, in order to be highly efficient in the reduction of nitrogen oxides, must mix homogeneously with the exhaust gas flow.

A pump that is connected to the DEF tank provides the desired injection pressure. It is directly controlled by the Engine Control Unit (ECU) or, as an alternative, by a dedicated control unit integrated in the dosing system, called Dosing Control Unit (DCU). The communication between the two control units is in this case implemented via Controller Area Network (CAN) line [1]. The pressurization system requires, in addition to a dedicated control system that monitors and coordinates the operation at the injection pressures, a diagnostic system that can identify pre-

determined faults. The recovery actions are designed to ensure full compliance with the standards imposed by the law and, at the same time, to guarantee preservation of the system itself and of its components. For these reasons, a model of the DEF supply system is very useful during the development of a new system. It can be used for testing the control strategies to be implemented in the real time controller, as also mentioned in [2]. A complete model of the SCR after-treatment system was previously developed by some of the authors of this paper, to support simulation and testing during the development phase [3]. In this work, after a brief description of the operation of the SCR system and its layout, the activities carried out to develop a zero-dimensional model of the Urea Delivery Module (UDM) for SCR catalytic converter, applicable to a wide range of diesel engines, from Light-Duty vehicles to Off-Road applications, are described. The development phase was characterized by the identification of the pressurization system model parameters, followed by the validation of the 0-D, control-oriented model. The second part of the paper presents some examples of the diagnostic strategies that were tested and validated in the Software In the Loop (SIL) environment.

SCR: SYSTEM OVERVIEW

Generalities

The DEF is produced on industrial scale in accordance with ISO 22241 and DIN V 70070-CEFIC and regulations for the proper functioning of the SCR system. The solution has the composition listed in Table 1 [4].

Table 1. DEF Composition

Component Name	CAS Number	Chemical Formula	%	CE Classification
Water	7732-18-5	H ₂ O	67.5	231-791-2
Urea	57-13-6	(NH ₂) ₂ CO	32.5	200-315-5

In nature it occurs as a colourless, odourless, non-hazardous to humans, liquid, with the physical properties listed in Table 2.

Table 2. DEF Physical Properties

pH	9.5 - 10 (basic)
Boiling Point	103 °C (decomposition temperature)
Freezing Point	- 11.5 °C
Vapour Pressure	6.3984 kPa (48 mm Hg) (at 20 °C)
Density	1.09 g/cm ³ (at 20 °C)
Thermal Conductivity	~ 0.570 W/m·K (at 25 °C)
Viscosity	~ 1.4 mPa·s (at 25 °C)

There are no specific problems related to transport in vehicles, and it does not require any special storage conditions. One of the characteristics to be carefully considered is the freezing point, located at temperatures easily achievable worldwide, especially in the winter season. To prevent solidification, many commercial systems perform an active heating of the ducts that contain the DEF, thus allowing operation at temperatures far below the freezing point. In addition to

this, they are typically provided with a system for thawing the tank and pump content, in order to liquefy and thus to make available to the injection system a certain quantity of DEF, in conditions of external critical temperature, within a certain given time limit, as specified by regulations. Another critical aspect is the tendency of the DEF solution to create solid deposits, which could clog the injector, if not properly filtered or removed.

The DEF delivery system is, as already mentioned, designed and controlled in order to reduce NO_x emissions. When the concentration of NH₃ in the catalytic converter is estimated insufficient for the reduction of NO_x, the proper amount of DEF is injected into the exhaust gas through an injector, placed immediately upstream of the catalytic converter, and oriented so as to ensure a proper distribution of urea and water particles into the main flow. The pressure in the injection system is generated by a volumetric pump driven by a DC motor, and it is usually controlled at a constant value. A plausible DEF injection pressure range is currently between 6 and 10 bar.

SCR System Layout

The SCR system developed for mobile applications, considered in this work, consists of (Figure 1) [5]:

1. DEF tank
2. Urea Delivery Module (UDM), composed of:
 - a. DC Motor
 - b. Pump
 - c. Zero delivery valve
 - d. Heater(s)
 - e. Filters
 - f. Pressure sensor
 - g. Level sensor
 - h. Quality sensor
 - i. Temperature sensor
3. Dosing Valve (DV), made up of:
 - a. Injector
 - b. Passive cooling heat sink
4. Mixer
5. Thermochemical reactor, made up of:
 - a. Outer casing
 - b. Structured support/underlayer
 - c. Oxide coating
 - d. Catalytic converter
6. Electrically heated pipe
7. NO_x sensors upstream (depending on system configuration) and downstream the catalyst
8. Exhaust gas temperature sensors
9. Dosing Control Unit (DCU) for UDM and DV management, interfaced with the ECU

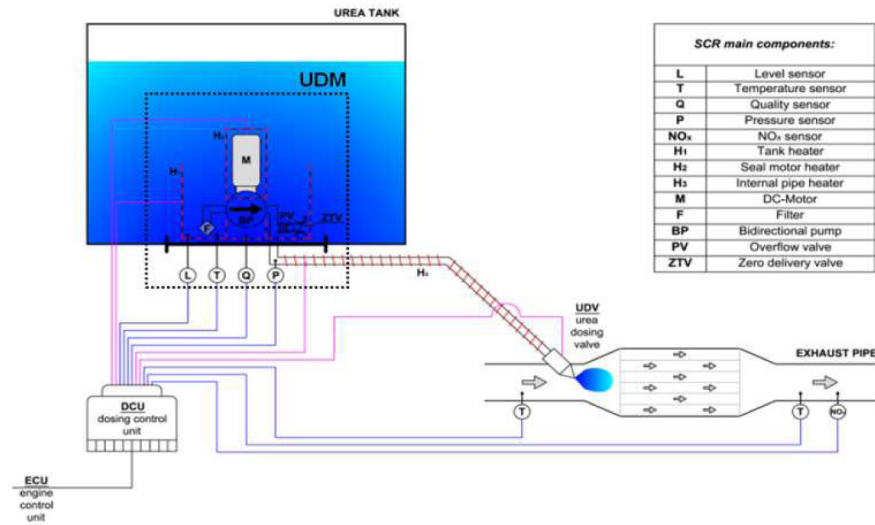


Figure 1. SCR System Layout.

The complete system, described above, was installed on board of two Euro 5 compliant light commercial vehicles, as described in [1]. Figure 2 shows the installation in one of those vehicles. After the setup, a calibration activity was carried on, then both vehicles were tested over the NEDC. They proved to be able to achieve Euro 6 emissions level, while at the same time guaranteeing a benefit on overall fuel consumption thanks to model-based engine control calibration.

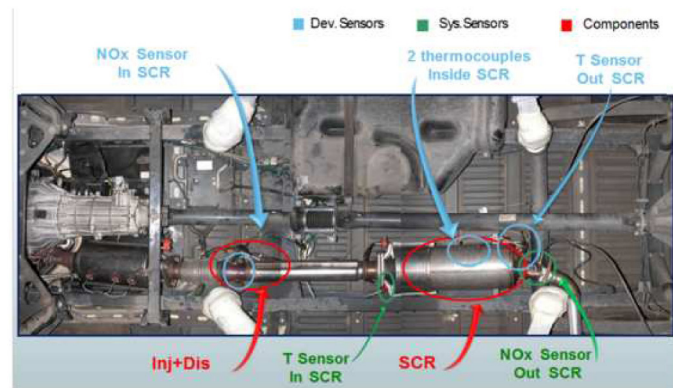


Figure 2. SCR system on board installation.

This paper is focused on the development of a control-oriented model of the urea solution pressurization system, strongly based on a physical description of the main electrical and fluid dynamics phenomena that characterize the UDM. The purpose of the model is to support the development, testing, and validation phases of the UDM control and diagnostic system.

UDM: PHYSICAL MODEL DESCRIPTION

The UDM includes several devices used to provide the correct injection pressure to the Dosing Valve (DV) and, at the same time, to monitor the status of the urea solution through the evaluation of some physical and chemical parameters. In this configuration, the UDM is placed inside the DEF tank, forming a single block for reductant storage and pressurization, and therefore minimizing the required

volume. The elements that form the UDM model are mainly those indicated by the letters a), b), c), e) and f) in section 2 of the previous paragraph list.

A schematization of the whole system is represented in Figure 3.

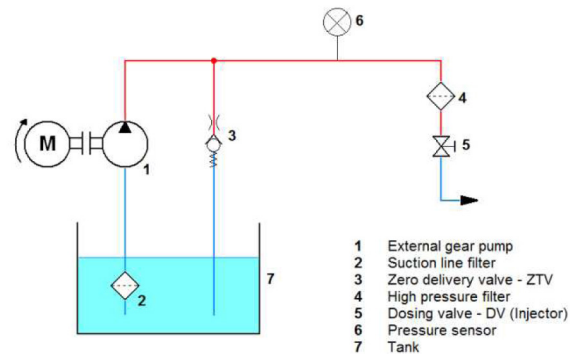


Figure 3. UDM Hydraulic System Schematization.

Hydraulic System Model

The output of the system will be, as anticipated, a pressurized DEF provided to the DV. The pressure level is the result of a mass balance between incoming and outgoing flow, respectively into and out of the branch of the plant downstream the pump. Considering the continuity equation in such branch, the resulting pressure level may be evaluated according to Equation (1).

$$p = \frac{\beta}{V_{pipe}} \cdot \int (Q_{pump} - Q_{valve} - Q_{inj}) dt + p_0 \quad (1)$$

in which:

- p = resulting pressure
- β = Bulk modulus
- V_{pipe} = pipe volume
- Q_{pump} = pump output flow



- Q_{valve} = recirculated flow
- Q_{inj} = injected flow
- p_0 = initial pressure

Notice that in Equation (1) it has been assumed infinite pipe stiffness and, for this reason, only the DEF Bulk modulus has been considered.

Electromechanical System Model

Considering the mechanical system as rotor and load, the torque balance according to Newton's second law yields:

$$J \cdot \frac{d\omega}{dt} = T_m - T_r = k_m \cdot i - b \cdot \omega - T_L \quad (2)$$

Where:

- J = resulting moment of inertia
- ω = angular velocity
- T_m = motor torque
- T_r = resistive torque
- k_m = motor torque constant
- i = current consumption
- b = equivalent viscous damping factor
- T_L = viscous friction (generated by the pump in rotation)

The electrical power balance may be expressed via Equation (3), by approximating the armature circuit of PMDC motor by the lumped parameter method [6]:

$$V_a = R_a \cdot i + L_a \cdot \frac{di}{dt} + k_V \cdot \omega \quad (3)$$

Where:

- V_a = supply voltage
- R_a = typical conductor-collector resistance
- L_a = inductance
- k_V = back electromotive force constant

The system of Equations (2) and (3) completely describes the dynamics of the pump, and thus allows determining, for given initial conditions, the resulting value of the propeller rotational speed.

UDM: PUMP EFFICIENCIES DETERMINATION

In order to implement a zero-dimensional modelling of the UDM system, it is essential to schematize the pump characteristics through its volumetric and mechanical efficiency curves. For this purpose, high frequency experimental acquisitions of motor current and

voltage supply signals have been carried out, together with the voltage signal of the pressure sensor located downstream the pump, while sweeping the pump operating range.

The angular velocity of the pump was determined by analysing the supply current spectrum via Fast Fourier Transform (FFT) techniques, suitably filtered by taking into account also the constructive characteristics of the propeller. The computation algorithm is based on the consideration that the supply current to the electric motor presents high frequency oscillations due to commutation events. For this reason, the high frequency component, related to the motor speed, is always superimposed on the armature current [7]. It has to be noted that the proposed method for determining the motor rotational speed is in principle only valid under steady state conditions, and this may introduce uncertainties during transients. The relationship between the frequency of current oscillations f and the angular velocity n , expressed in rpm, may be expressed as:

$$f = \frac{k \cdot s \cdot n}{60} \quad (4)$$

Where:

- k = number of commutation segments
- s = number of brushes

Pump Volumetric Efficiency

The pump volumetric efficiency can be defined as the ratio between actual and theoretical flow rate:

$$\eta_V = \frac{Q}{Q_T} = \frac{Q_T - \Delta Q}{Q_T} = 1 - \frac{\Delta Q}{Q_T} = 1 - \frac{\Delta Q}{(n/60) \cdot C} = f(C, \omega, \Delta P, \mu) \quad (5)$$

Where C is the pump capacity.

The DEF has a kinematic viscosity of about 1.27 cSt [4] and this explains why the volumetric efficiency, identified under different operating conditions, is quite low for the pump type considered, and particularly sensitive to pressure increase, as shown in Figure 4.

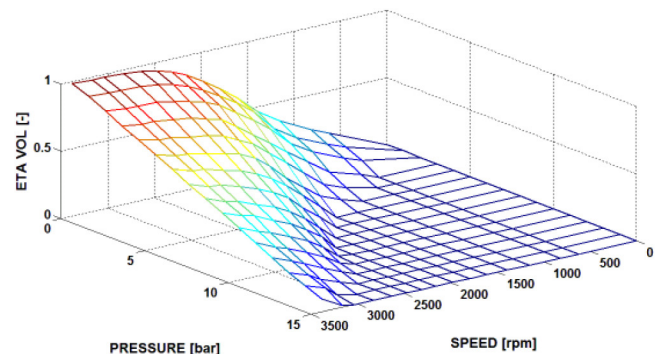


Figure 4. Experimentally Identified Volumetric Efficiency Map.