THE NOx EMISSION ESTIMATION BY THE ARTIFICIAL NEURAL NETWORK: THE RESULTS

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Abstract

The paper presents the preliminary investigations of nitric oxides (NOx) estimation from marine two-stroke engines. The Annex VI to Marpol Convention enforce to ship - owners necessity of periodical direct measurements of the NOx emission from the ship engines. It is very expensive procedure but with a low accuracy. Presented investigations show the possibility of estimation the NOx emission without direct measurements but using the artificial neural network (ANN). The paper presents chosen structures of ANN's usable to NOx emission estimation, the laboratory investigations and effects of estimation NOx emission. The paper reports the effects of investigations during different points of load the engine, with constant and changeable air/fuel equivalence ratio. The detailed results of measurement and calculation of NOx concentration in the exhaust gases of marine two-stroke diesel engine were presented. The results show that the multilayer perceptron neural network (MLP) is sufficient to NOx emission estimation during onboard exploitation. The MLP network with 15 neurons in the hidden layer has best accuracy for data sets collected during running the engine with speed equal 200 rpm and constant air/fuel equivalence ratio and for both considered speeds of the engine with changeable air/fuel equivalence ratio.

Keywords: *emission, NOx, nitric oxides, ANN, artificial Neural Network, perceptron, ship diesel engine*

1. Introduction

The International Maritime Organization introduced Annex VI to MARPOL 73/78 convention to prevent the sea environment of nitric oxides (NOx) contamination. This Annex forces ship owners to limit NOx emission from ship engines. The allowable level of this emission is defined in NOx Technical Code [1]. According to this Code, every introduced to operation onboard engines above 130 [kW] are obligated to have the valid certificate confirming the acceptable emission of the NOx. If ship engines are subjected some alterations during their operation period, they will have to extend such a certificate. Its prolonging consists in checking of parameters and structural parts of the engine influencing the NOx emission. Changes of these could entail the necessity of carrying out the direct onboard measurements. Usually it's very expensive and labor absorbing process. According to these regulations, acceptable levels of emission even about 10% comparing with methods using on the shore. For the heavy fuel, these regulations allow to exceed this limit even up to 15%.

In [2] I proposed a method of the NOx estimation from the onboard diesel engine based on the measurements of working engine parameters like pressures, temperatures, etc. Moreover, I assume that these parameters measured in the standard equipped engine room are sufficient for developing the mentioned method [3]. This, in turn, requires developing the appropriate model connecting these parameters into a function allowing for assessing a level of the NOx emission. In order to reduce the high cost of modeling the artificial neural network (ANN) is proposed.

The laboratory study to collect the appropriate enter, test and validation data will present in this paper. The paper reports the results of the estimation of the NOx emission from the marine two-stroke engine with using considered ANNs. The results during the engine operation with inefficient fuel system will present also.

2. Artificial neural network description

During the preliminary investigations [2] both, the MLP and RBF networks are considered. The networks consist of 15 input neurons in input layer for 15 enter data, one neuron in output layer for NOx emission estimation and neurons in one hidden layer.

Based on the analyze of the NOx producing in the combustion chamber of the marine diesel engine the following input data are chosen:

- a temperature of the scavenging air,
- humidity of the scavenging air,
- a fuel consumption of the engine,
- an air/fuel ratio,
- a speed of the engine,
- a mean cylinder pressure,
- a maximum cylinder pressure,
- a crankshaft position at the maximum cylinder pressure,
- a maximum injection pressure,
- a crankshaft position at the maximum injection pressure,
- a temperature of the fuel before the injecting pump,
- a temperature of the exhaust gas,
- a temperature of water in the inlet of the cooling system,
- a temperature of water in the outlet of the cooling system,
- a pressure of water in the cooling system.

The number of neurons in the hidden layer was changed from 10 to 20 for MLP network and from 10 to 80 in RBF network. The logistic function as an activation function was used and the data sets before using were standardized to values from 0 to 1. The learning rate was set on 0.01.

The learning process for all considered ANNs consists of back propagation process, the conjugate gradient method, and the 5 times repeated cross validation. The description of the learning process is presented in [2]. The input, validate and the test data were collected during direct measurements on a two stroke, one cylinder, loop scavenged, laboratory engine.

3. The laboratory test description

I carried out the laboratory test using the L - 22 engine installed in the laboratory of Gdynia Maritime University. It is a crosshead, single-cylinder, and two - stroke diesel engine with loop scavenging. Roots' blower, driven independently by an electric motor with an infinitely variable adjustment of rotational speed charges this engine. The tested engine is loaded by a water brake. Basic parameters of the L - 22 engine are presented in Tab. 1. and a schematic diagram of the laboratory stand is presented in Fig. 1.

The measuring equipment installed on the tested engine permitted on the continuous recording of the most measured results with samplings approximately 0.5 second.

According to the part - 1 of the paper the quantity of NOx emitted from engine depends on temperature and pressure of combustion, time of combustion and composition of combusted mixture. The temperature and pressure of combustion is determined by parameters of the injection process, pressures in the combustion chamber, temperatures and pressure of the cooling system and temperatures of the fuel and the exhaust gases. Time of combustion is determined by speed of the engine. In the same timing of the exhaust valve, increasing of speed of the engine causes decreasing of combustion time. Composition of mixture is changed by changing the air/fuel equivalence ratio with the same combusted fuel.

The fundamental stage of our research consists of 10 observations. We loaded the tested engine in a range from 25% to 75% of its nominal load with two rotational speeds namely 200 and 360 rpm. The larger load of the engine was not possible because of the admissible load of the used water brake and too small efficiency of the Roots' blower for keeping of steady air/fuel

equivalence ratio. The measurements have been carried out for the working engine with:
- its constant rotational speed and changeable loads for a constant value of air/fuel equivalence ratio,
- its constant rotational speed and load for changeable values of air/fuel equivalence ratio.

Tab. 1. Parameters of the test engine

Nominal Power [kW]	73.5
Rotational Speed [rpm]	600
Cylinder bore [mm]	220
Piston Stroke [mm]	350
Compression Ratio [-]	18.5

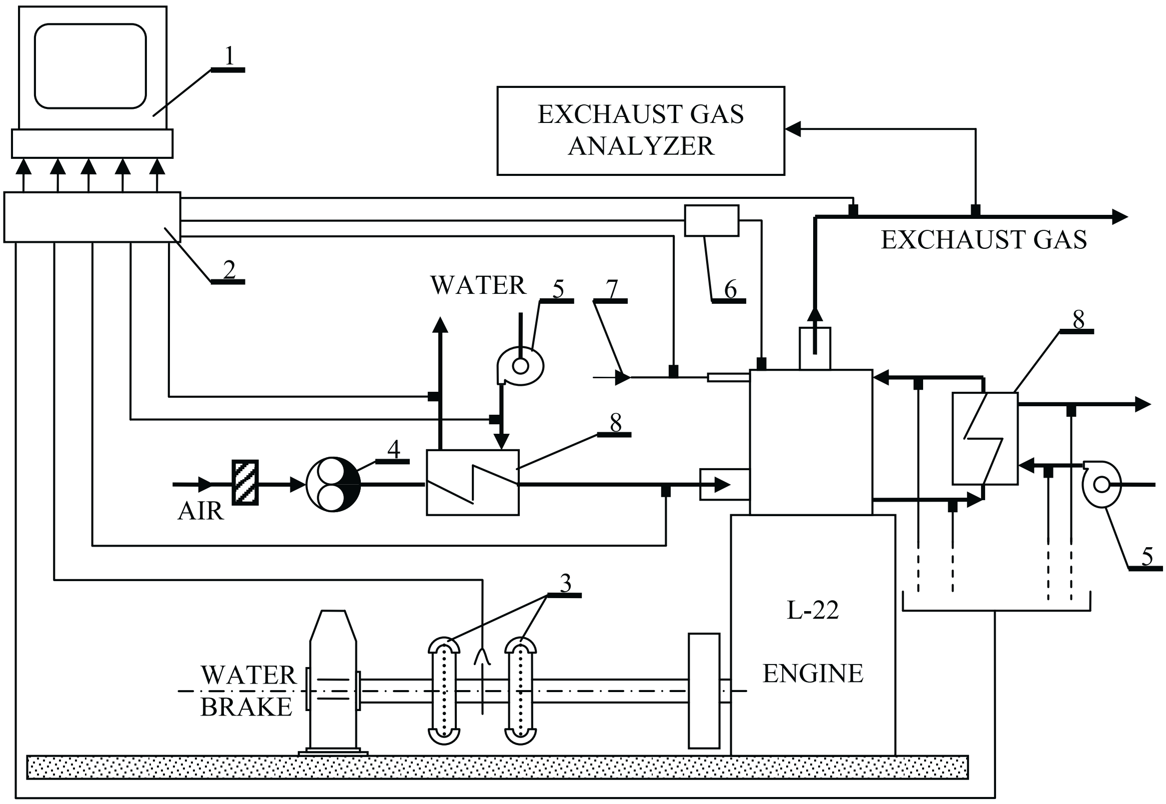

Fig. 1. A schematic diagram of the laboratory stand: 1 - a recording computer, 2 - A/C converter, 3 - rubber flexible couplings, 4 - Roots' blower, 5 - a fresh water pump, 6 - an electronic indicator of pressure, 7 - fuel installation, 8 – a heat exchanger

In this research, the air/fuel equivalence ratio [4] was understood as a ratio of a mass amount of air delivered to a cylinder to amount of air necessary to combustion of a fuel dose injected to this cylinder whereas the changeable loads realized by means of using a water brake. Values of the engine loads (M) described like percent of nominal momentum Mn and rotational speeds (n) are presented in Tab. 2.

Tab. 2. Values of the tested engine loads and rotational speeds

No.	1	2	3	4	5	6	7	8	9	10	11
M [% of Mn]	75	70	65	60	55	50	45	40	35	30	25
n [rpm]	200										
No.	12	13	14	15	16	17	18	19	20	21	22
M [% of Mn]	75	70	65	60	55	50	45	40	35	30	25
n [rpm]	360										

During our research, the engine has been supplied by the diesel fuel with its known specification, obtained from its producer (Lotos EuroDiesel EKO Z with density at 15ºC equal 829.6 kg/m^3).

4. The results of NOx emission estimations by ANN's

The results presented in the part - 1 of the paper shows that all considered ANN's have mean error presented like [%] of NOx concentration in [ppm] (particles per million) less than 2%. Nevertheless the MLP type of networks are simplest and more accuracy. According to IMO regulations [1] that error is permissible to onboard estimation of NOx emission from marine diesel engines. Unfortunately the alternative method of NOx emission estimation must be safe for all points of marine engine load during onboard exploatation.

The Fig. 2. presents only the maximum errors (above and below the measured NOx concentrations) for all considered MLP and RBF networks.

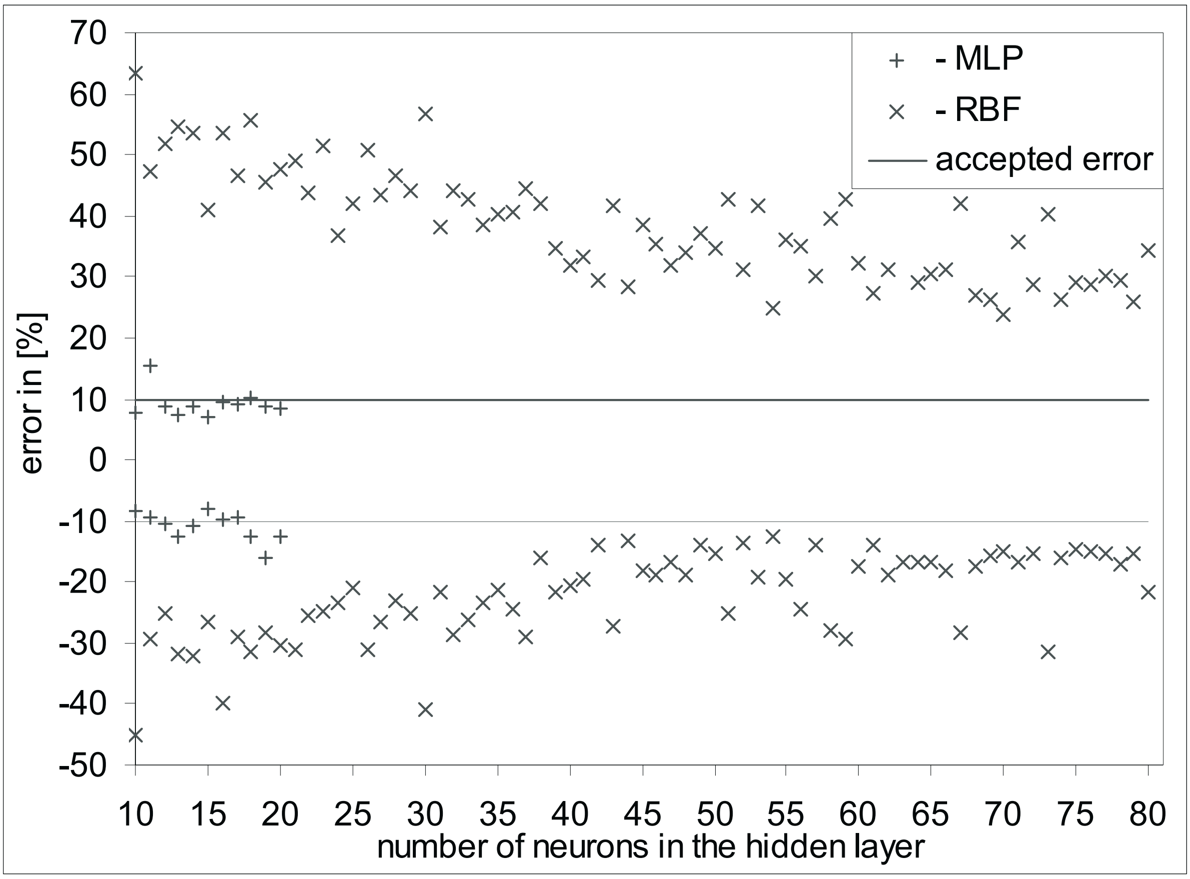

Fig. 2. The maximum error (above and below the measured NOx emission) for all considered networks

According to presented in Fig. 2. results, all RBF networks have at least one result with error excided 10% from measured results for all considered points of load of the laboratory engine. Moreover, only four MLP networks have results, from among which no one excided 10% of error. There are the MLP networks with 10, 15, 16, and 17 neurons in the hidden layer. The detailed results for these MLP networks are presented in Fig. 3.

The results presented in Fig. 3. confirm usefulness of considered MLP networks to NOx emission estimation onboard according to IMO regulations.

The Fig. 4. and Fig. 5. shows the results of measurements of NOx concentration during run the engine with constant air/fuel equivalence ratio and constant rotational speed and changeable engine load. Simultaneously the effects of NOx concentration modeling by considered four MLP networks are presented also. According to these results increasing the load of the engine cause increasing of NOx concentration in the exhaust gases. The same tendency is perceptible for modeling results. The best network for this stage of investigations is network with 10 neurons in hidden layer - MLP(10). The maximum error of this network is 7.4% for both rotational speeds of the engine. The MLP(15) has better accuracy for engine speed equal 200 rpm (6.7%) but for 360 rpm the maximum error for this network is 8.2%. The best accuracy for engine speed equal 360 rpm has network MLP(16) (7.2%).

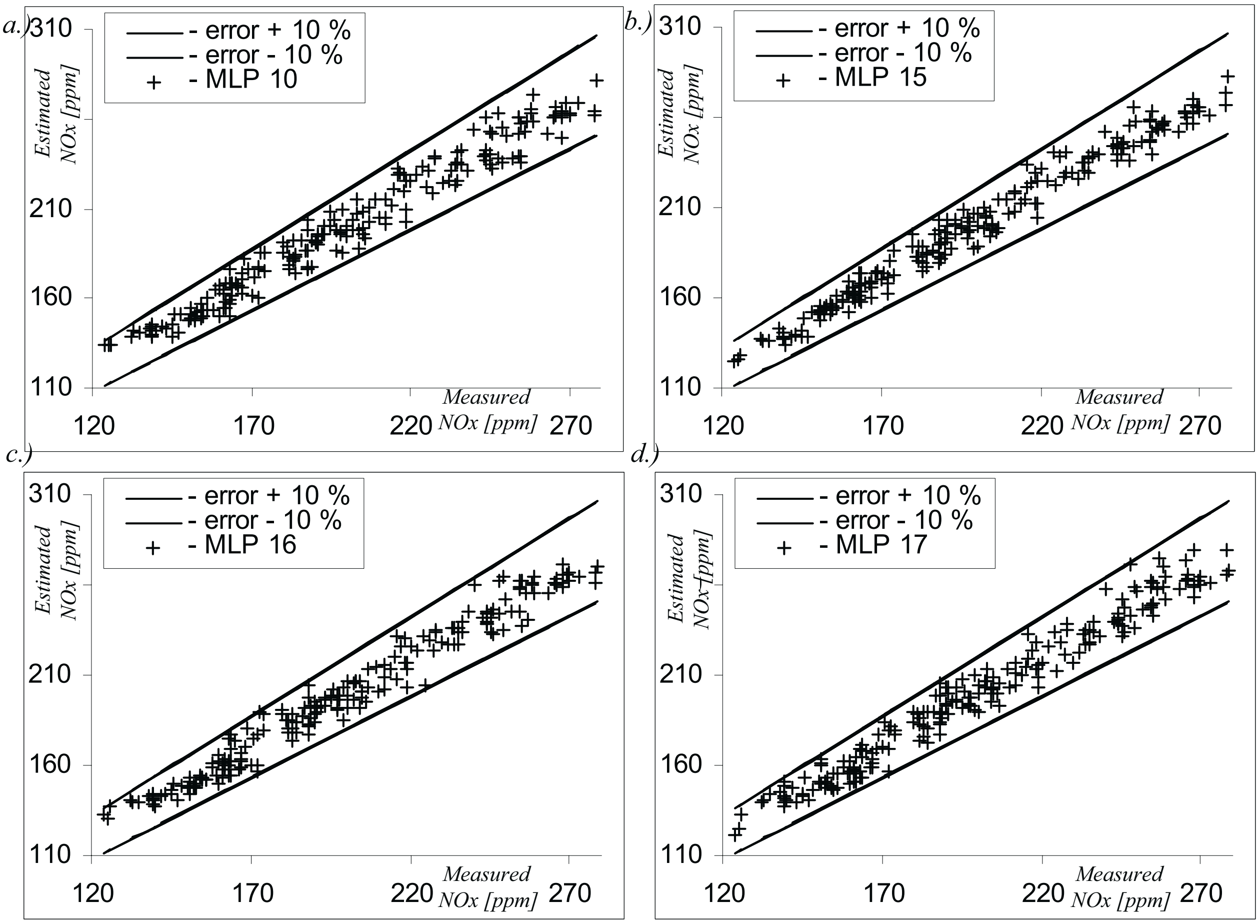

Fig. 3. The detailed results for the MLP networks with: a.) - 10, b.) - 15, c.) - 16, and d.) - 17 neurons in the hidden layer

The Fig. 6. and Fig. 7. shows the results of NOx concentration in the exhaust gases measurement and ANN's modeling for the second stage of the investigations. During this study the engine run with constant load (25% of maximum load) and constant rotational speed and changeable air/fuel equivalence ratio. The results of measurements show decreasing of NOx concentration in the exhaust gases. The results of modeling confirm this tendency only for speed of the engine equal 200 rpm.

The reason of this situation may to be too little spread of air/fuel equivalence ratio for running the engine with speed equal 360 rpm or small quantity of learning data sets. The best network for this stage of investigations is MLP(15) network. The maximum error for this network is 8.2% for 200 rpm engine speed and 4.8% for 360 rpm engine speed respectively. The biggest maximum error has MLP(17) network for engine speed equal 200 rpm (9.4%) and MLP(10) network for engine speed equal 360 rpm.

According to these results most appropriate network to NOx concentration estimation for two stages of the investigations is MLP(15) network, but to improve the accuracy of the model thorough investigations must be done in the future. Especially it's important to collect larger data set to learning process.

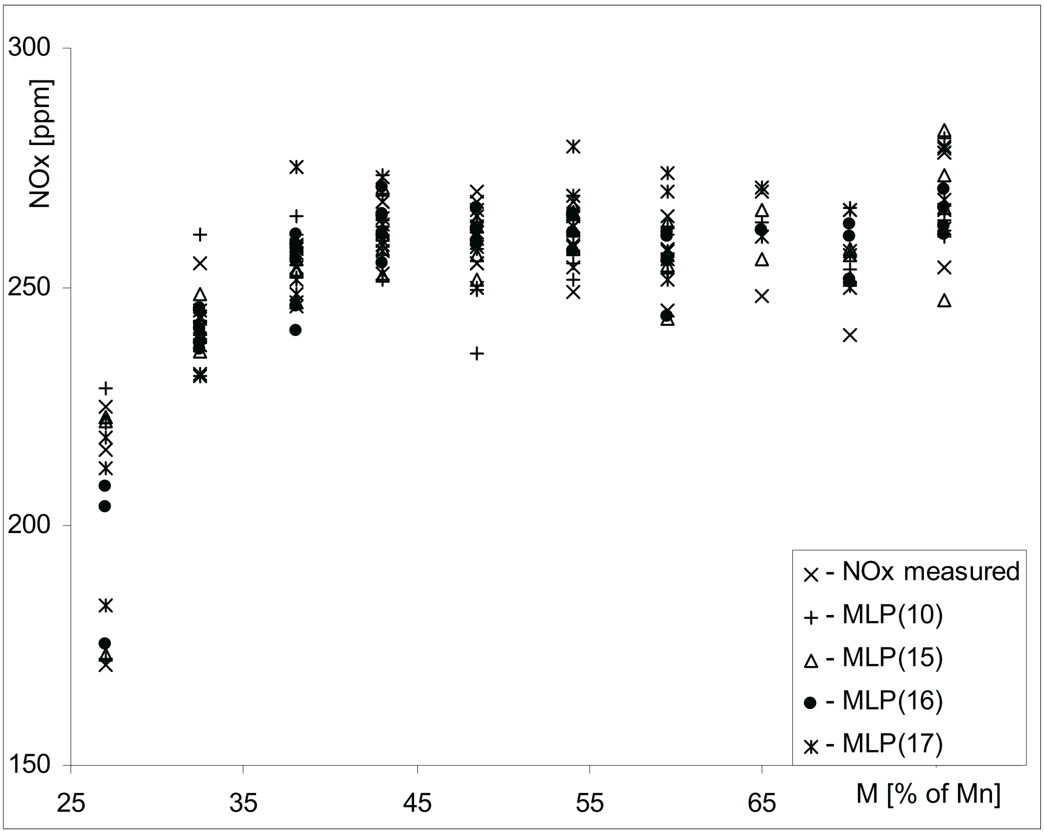

Fig. 4. The results of NOx concentration measurements and ANN's modeling during run the engine with 200 rpm and constant air/fuel equivalence ratio

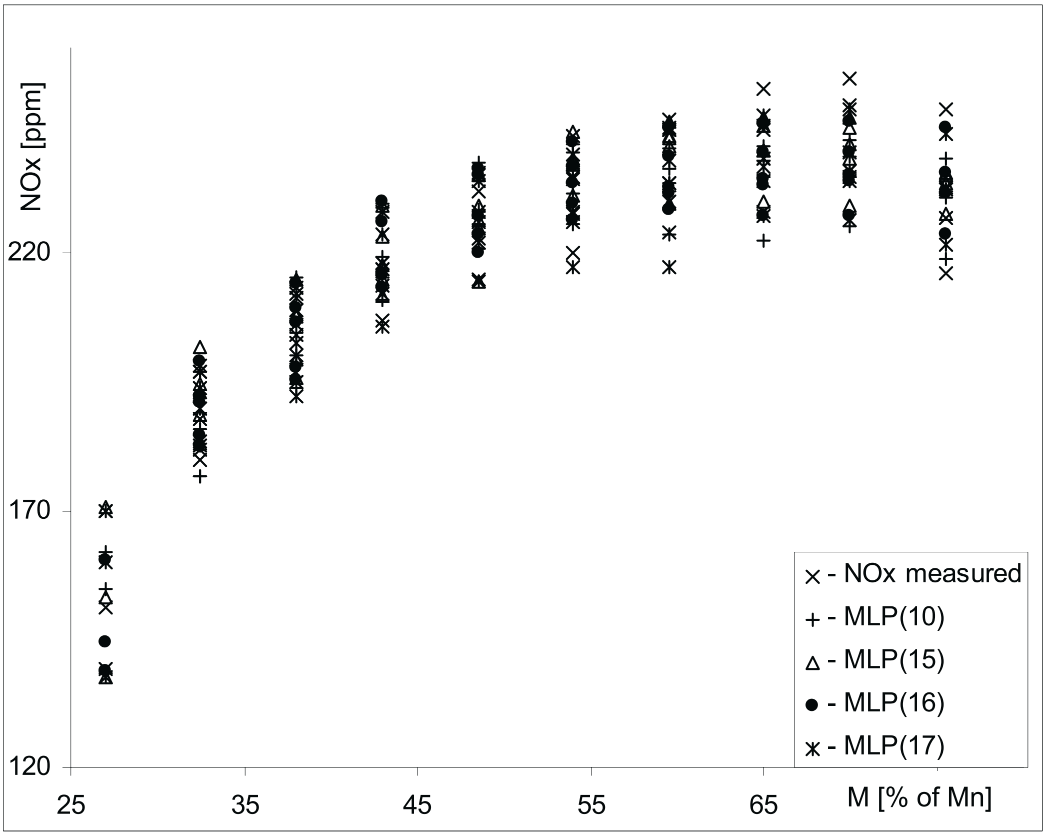

Fig. 5. The results of NOx concentration measurements and ANN's modeling during run the engine with 360 rpm and constant air/fuel equivalence ratio

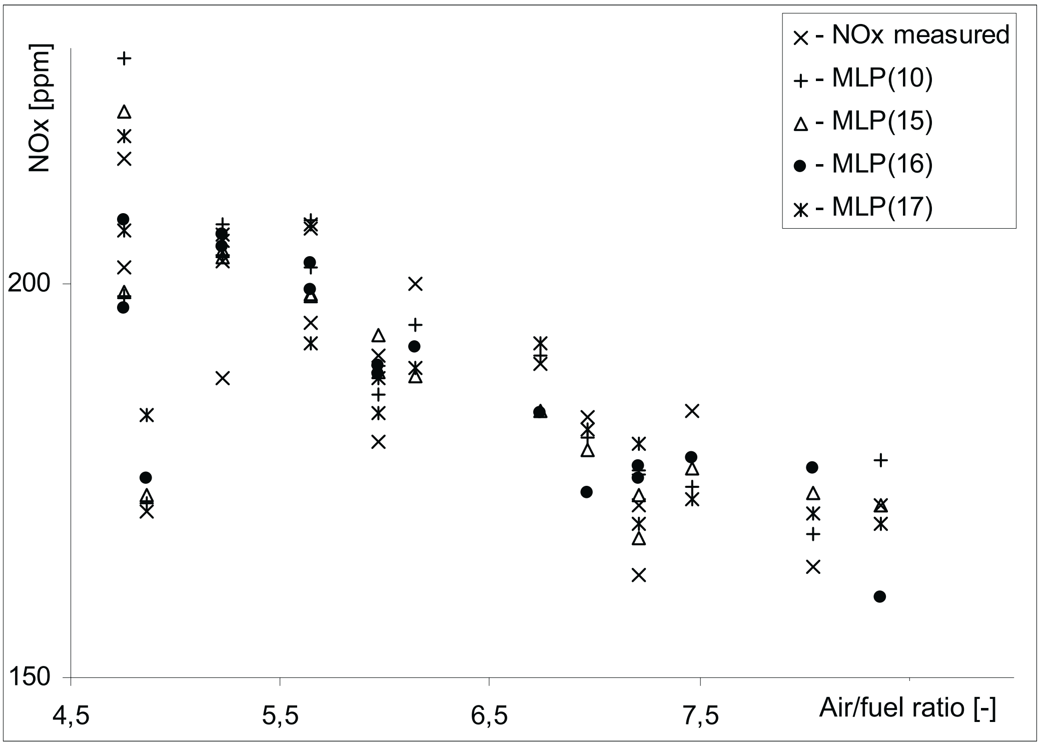

Fig .6. The results of NOx concentration measurements and ANN's modeling during run the engine with 200 rpm and changeable air/fuel equivalence ratio

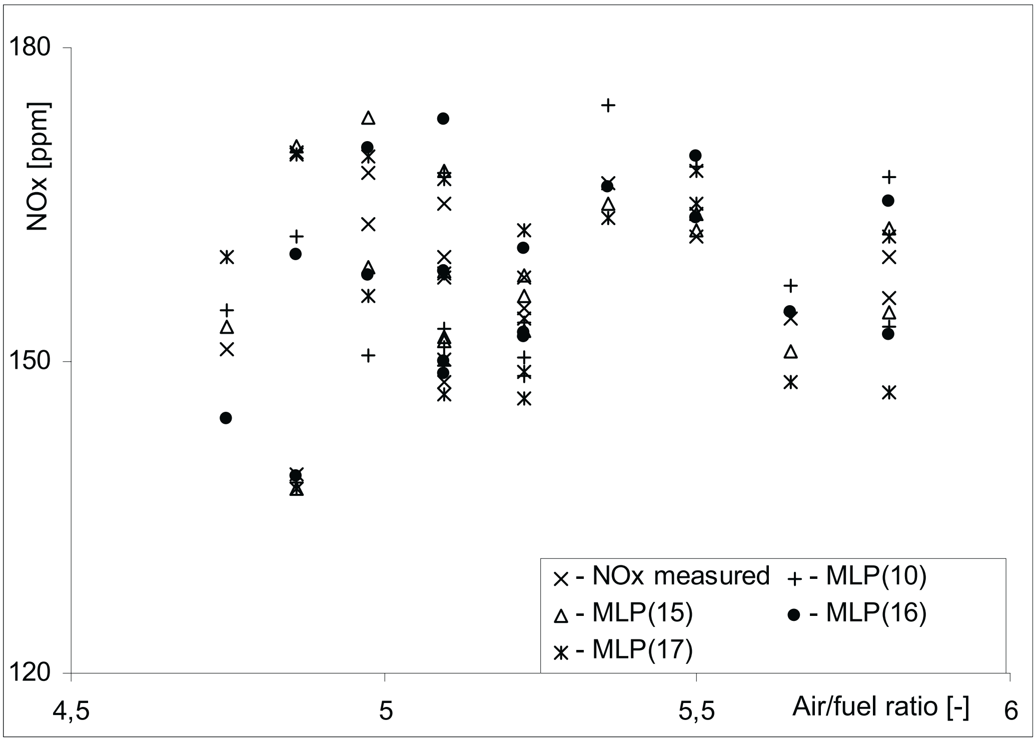

Fig. 7. The results of NOx concentration measurements and ANN's modeling during run the engine with 360 rpm and changeable air/fuel equivalence ratio

5. Conclusions

The paper describes the results of measurements and calculations of NOx concentration in the exhaust gases of marine two stroke diesel engine. The presented results of this work enable the following conclusions to be drawn:

- all considered RBF networks have maximum errors biggest than permissible in the IMO regulations,
- only four MLP networks have maximum errors for all considered points of load the engine littlest than 10%,
- the results of measurements show decreasing of NOx concentration in the exhaust gases, but the results of modeling confirm this tendency only for speed of the engine equal 200 rpm. The reason of this situation may to be too little spread of air/fuel equivalence ratio for running the engine with speed equal 360 rpm or small quantity of learning data sets,
- most appropriate network to NOx concentration estimation for two stages of the investigations is MLP network with 15 neurons in the hidden layer, but to improve the accuracy of the model thorough investigations must be done in the future.

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