PERFORMANCE AND EMISSION CHARACTERISTICS OF OFF-ROAD DIESEL ENGINE OPERATING ON RAPESEED OIL AND PETROL BLENDS

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Abstract. This article presents the bench testing results of a four stroke, four cylinder, direct injection, unmodified, naturally aspirated diesel engine operating on neat rapeseed oil (RO) and its 7.5 vol % blend with petrol (PRO7.5). The purpose of this research was to investigate the effect of petrol addition in the RO and preheating temperature on biofuel viscosity, brake mean effective pressure developed by the engine, its specific fuel consumption, the brake thermal efficiency and emission composition changes, including NO, NO_2, NO_x, CO, CO_2, HC and smoke opacity of the exhausts. It was determined that addition in the RO 7.5 vol % of petrol the blend viscosity at ambient temperature of 20 ˚C diminishes by 31.7 % and the biofuel flow in the fuelling system improves. During operation of the fully loaded engine under constant air-to-fuel equivalence ratio, λ=1.6, at the maximum torque 1800 min^{-1} and rated 2200 min^{-1} speed blend PRO7.5 ensures the brake mean effective pressure lower correspondingly by 2.6 % (*bmep*=0.750 MPa) and 0.5% (*bmep*=0.736 MPa) than that of neat RO case (0.770 and 0.740 MPa). The bsec at maximum torque (9.34 MJ/kWh) and rated power (9.08 MJ/kWh) determined when fuelling the engine with blend PRO7.5 is higher by 2.1 % and lower by 0.7 % and the brake thermal efficiency lower by 1.5 % and higher by 0.3 %, respectively, comparing with that of neat RO. The test results indicate that when running of the fully loaded engine at rated 2200 min^{-1} speed, petrol addition in the RO up to 7.5 vol % increases NO (18.2 %), NO_2 (2.8 times), NO_x (19.6 %), NO_2/NO_x (2.4 times), CO (33.4 %), HC (by 9-11 ppm) emissions and exhaust gas temperature (2.4 %) and diminishes simultaneously CO_2 (2.6 %) emission and smoke opacity (2.4 %) of the exhausts.

Key words: diesel engine, rapeseed oil, petrol, effective parameters, emissions, smoke opacity

Introduction

One of the biggest problems of the 21st century is linked with eventual depletion of fossil fuels, growing ambient air pollution and urgent concern about climate changes occurring because of the increased CO_2 emissions and global warming that all together provoke frequent hurricanes followed by heavy rains and deadly floods. In order to extend environment friendly energy sources and suspend the growing air pollution, special interest among researchers has been currently focused towards reducing dependence on fossil fuels replacing them as much as possible by renewable energy, which could diminish the carbon dioxide CO_2 emission in a global cycle and so called “green-house” effect. Environmental advantages that could be utilised by using cleaner energy sources and biofuels would be essentially important for reducing air pollution caused by transport and agricultural sectors in order to the amount of the exhaust gases should comply with the stringent EU emission standards.

To achieve this goal, along with popular in Europe RME, neat rapeseed oil (RO) could also be used for the local tractor fuelling. Potential advantages and disadvantages of the RO as biofuels variety extender have been elucidated in investigations [1-3]. RO is also sulphur free (0.04-0.002 %), during short term application suggests a bit higher maximum brake thermal efficiency (*bte*=0.38-0.39) than that of the diesel fuel (0.37-0.38), by 40.5 % to 52.9 % lower CO, 27.1 % to 34.6 % lower smoke opacity and close to zero (2-3 ppm) HC emissions [4]. This environmental friendly and renewable fuel is less dependent on the fiscal policy and more economically attractive especially when used as sub-product extracted during production of oilcakes for animal farming. Bearing in mind that inexpensive low energy cold-pressing (<50 ˚C), filtering, sedimentation and decanting facilities could be arranged in remote rural areas, the usage of neat RO for agricultural tractors fuelling can improve cost efficiency based on lower production and transportation prices and increase its competitiveness on the market compared with RME.

However, the main problem associates with high viscosity of RO that at ambient temperature of 20 ˚C is about 13 times higher than that of mineral diesel fuel. High viscosity of neat RO may aggravate oil flow in the fuelling system worsening injection pump performance and fuel spray patterns, its lower volatility and higher both flash point (220-280 ˚C) and auto-ignition temperature (320 ˚C) may affect biofuel evaporation and combustion, engine performance efficiency, smoke of the exhausts and related emissions [3, 4].

According to the investigations [1], the viscosity of RO could be diminished by means of blending it with mineral petrol. In contrast to ethanol [5], the miscibility of petrol with RO (PRO) is excellent and, being by 4.3 % lighter than ethanol, petrol may reduce RO viscosity even more efficiently. It is worth noticing, that blends PRO are more stable than ERO and no phase stratification takes place during storage that lets regard them as potential biofuels variety extenders.

For RO blending purposes the mostly suitable would be the low octane petrol (grade A-76/80), which exhibits cetane number ranging from 20 to 25, i.e. approximately three-fold higher than that of ethanol, and auto-ignition temperature a little bit lower (300 ˚C) comparing with that of RO. It is also important for facilitating auto-ignition of rapeseed oil, that the addition of petrol extends evaporation temperature range from 35 to 195-210 ˚C in comparison with a single boiling point (78 ˚C) at the start of the distillation curve of ethanol. The earlier start of petrol evaporation may intensify the preparation of combustible mixture and facilitate auto-ignition of heavy and low volatile RO fractions since this temperature is far below the starting point of distillation curve of rapeseed oil.

The purpose of the research is to investigate the effect of petrol addition in the RO and preheating temperature on blend viscosity and conduct comprehensive bench tests to study the brake mean effective pressure, brake specific energy consumption, brake thermal efficiency, smoke opacity of the exhausts and emission composition changes, such as nitrogen oxides NO, NO_2, NO_x, carbon monoxide CO and dioxide CO_2, and total unburned hydrocarbons HC when fuelling the engine alternately with neat rapeseed oil and its 7.5 vol % blend with petrol over a wide range of loads and speeds.

Objects, apparatus and methodology of the research

Tests have been conducted on a four stroke, four cylinder, 59 kW DI diesel engine D-243. In order to increase the flow rate of viscous RO the fuelling system was modified by means of installing of two joined in parallel honeycomb shaped design fine porous fuel filters. The fuel was delivered by an in line fuel injection pump thorough five holes of the injection nozzles with the initial fuel delivery starting at 25˚ before top dead centre. The needle valve lifting pressure for all injectors was set to 17.5±0.5 MPa.

Load characteristics of the engine were taken at the revolution frequencies 1400, 1600, 1800, 2000 and 2200 min^{-1} when running it alternately on neat RO and its 7.5 vol % blend with petrol. The engine load characteristics were taken with a gradual increase of torque from the point that was close to zero up to its maximum value of 290-310 Nm. This means that the effective power of the engine at rated 2200 min^{-1} speed had been changed from the minimum up to 110 % of its rated value.

The torque of the engine was measured with 110 kW electrical AC stand dynamometer and the revolution frequency of the crankshaft was determined with the universal ferrite-dynamic stand tachometer TSFU-1 and its counter ITE-1 that guarantees the accuracy of ±0.2 %. The fuel mass consumption was measured by weighting it on the electronic scale SK-1000 with a definition rate of ±0.05 g and the volumetric air consumption was determined by means of the rotor type gas counter RG-400-1-1.5 installed at the air tank for reducing pressure pulsations. The amounts of carbon monoxide CO (ppm), dioxide CO_2 (vol %), nitric oxide NO (ppm), nitrogen dioxide NO_2 (ppm) and the residual content of oxygen O_2 (vol %) in the exhausts were measured with the Testo 33 gas analyser. The concentration of unburned hydrocarbons HC (ppm vol) and the residual oxygen O_2 (vol %) content in the exhaust manifold were determined afterwards with a gas analyser TECHNOTEST Infrared Multigas TANK model 488 OIML. The smoke opacity D (%) of the exhausts was measured with the Bosch device RTT 100/RTT 110, the readings of which are provided as Hartridge units in scale *I* – 100 % with ±0.1 % accuracy.

In order to have adequate combustion preconditions and perform proper analysis of contribution of blend PRO7.5 to the production of harmful emissions, their changing behaviour under various speeds was determined at constant air-to-fuel equivalence ratios λ specified for light, λ=6.0, medium, λ=3.0, and heavy, λ=1.6, loads.

Results and discussions

It was determined that addition in the RO 7.5 vol % of petrol the oil viscosity at ambient temperature of 20 ˚C diminishes by 31.7% and makes easy rapeseed oil flow in the fuelling system. In order to improve further the filtration properties of RO and its 7.5 vol % blend with petrol the biofuel preheating in the heat exchanger can be used as supplementary measure. The test results indicate that heating from ambient conditions of 20 °C up to the temperature of 60 °C the viscosity of neat RO and blend PRO7.5 diminishes 4.2 and 3.7 times, respectively.

The test results confirm that when operating under constant air-to-fuel equivalence ratio λ=1.6 at the maximum torque mode 1800 min^{-1} and rated 2200 min^{-1} speed the fully loaded engine fuelled with blend PRO7.5 develops the same, 1.739-1.742 MJ/kg, energy content of fuel-rich mixture the brake mean effective pressure (bmep) is lower by 2.6 % and 0.5 % than that of neat RO. A little reduced power output can be attributed to cetane depressing properties of petrol [6] however the bmep developed by the fully loaded engine operating on blend PRO7.5 is much better at rated 2200 min^{-1} speed than that obtained previously when fuelling it with blend ERO7.5 [5].

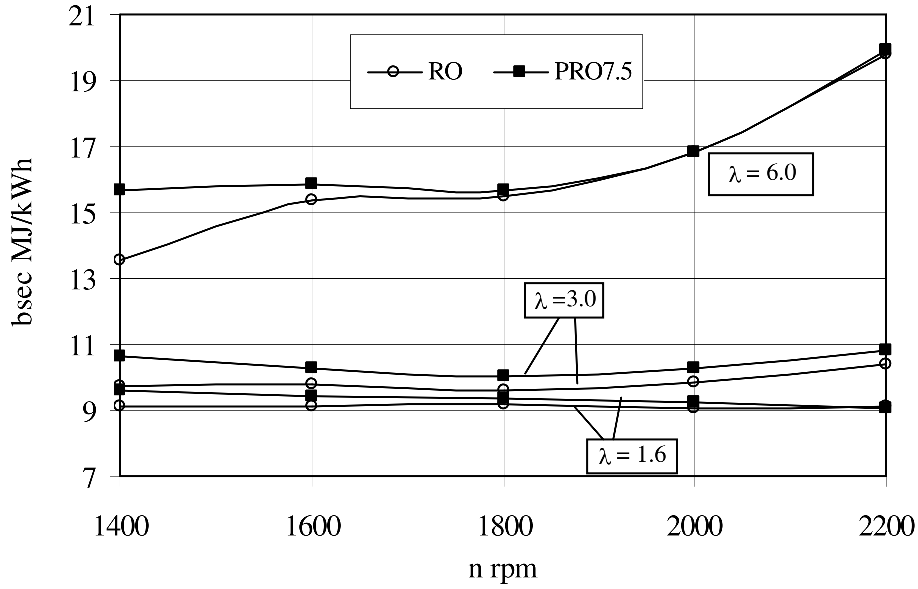

Fig. 1. **The brake specific energy consumptions (bsec) for various air-to-fuel equivalence ratios λ (loads) as a function of engine speed (*n*)**

Dependencies of the brake specific energy consumption (bsec) in MJ/kWh as a function of speed determined during engine operation on neat RO and blend PRO7.5 for three typical loading conditions characterised by air-to-fuel equivalence ratios λ=6.0, 3.0 and 1.6 have been superimposed as shown in Fig. 1. Analysing the test results one should bear in mind that blend PRO7.5 contains a little less 10.0 % of the fuel conserved oxygen against that 10.8 % based in the neat RO. Taking into account that the stoichiometric air-to-fuel equivalence ratio for oxygen free petrol is considerably higher (14.55) than that for neat RO (12.63), this is translated into slightly higher 12.77 the stoichiometric air-to-fuel equivalence ratio of blend PRO7.5. Net heating value of petrol is also better (42.88 MJ/kg) comparing with that of rapeseed oil (36.87 MJ/kg) and after mixing RO with petrol the calorific value of the tested blend PRO7.5 was increased to 37.32 MJ/kg.

As it follows from the analysis of the data, the bsec of blend PRO7.5 for light, medium and heavy loads is higher correspondingly by 15.9 %, 8.9 % and 5.3 % at low 1400 min^{-1} speed. Differences in the bsec between neat RO and blend PRO7.5 have a tendency to diminish with revolutions and the bsec curves for easy loaded engine, λ=6.0, coincide actually when rotation speed increases up to 2000 min^{-1} and beyond. When operating under medium load, λ=3.0, the bsec graph of blend PRO7.5 proceeds along speed axis at higher from 8.9 % to 3.8 % level relative to that of neat RO. After transition to heavy loading conditions, λ=1.6, the differences between the both biofuels tested become minor and the bsec of blend PRO7.5 from higher by 5.2 % and 2.1 % levels determined for low 1400 min^{-1} and maximum torque corresponding 1800 min^{-1} speeds diminishes to lower by 0.7 % level for rated 2200 min^{-1} speed. These results indicate better energy conversion efficiency in the case of fuelling the engine with blend PRO7.5 and differ actually from previous test results [5], where the bsec of the fully loaded engine run on blend ERO7.5 increased against that of neat RO by up to 8.3 % for rated 2200 min^{-1} speed.

The NO and NO_x emissions behaviour depends much on the diesel engine performance conditions [6], the feedstock oil used for engine fuelling and iodine number [7], the composition and chemical structure of the fatty acids [8] as well as on variations in actual fuel injection timing advance and auto-ignition delay caused by changes in physical properties, such as the effect of bulk modulus, viscosity and density of the biofuel [9]. Since the auto-ignition delay and combustion peculiarities of fuel premixed have significant influence on cylinder maximum gas pressure and temperature, variations in fuel cetane number ant its actual start of injection may lead to the corresponding changes in NO and NO_x emissions.

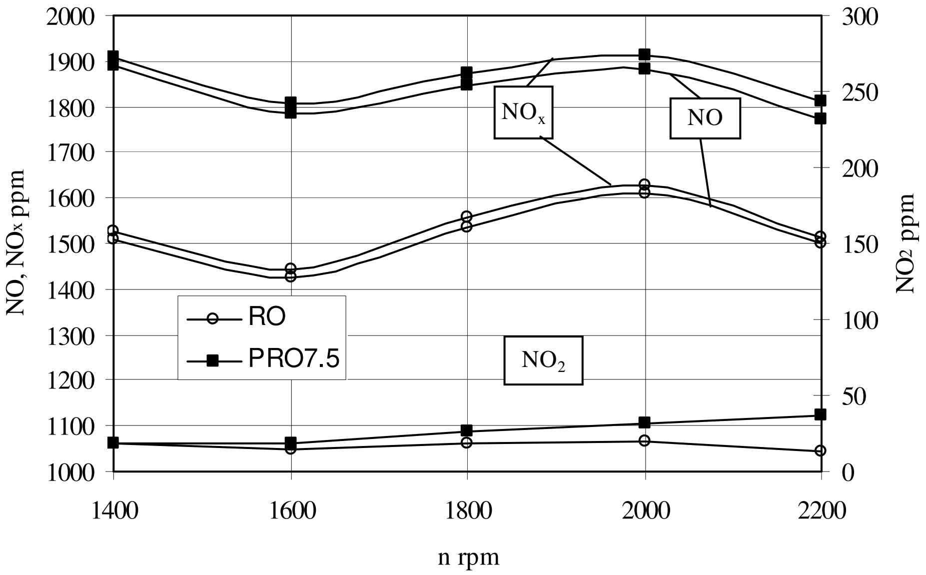

Fig. 2. **The maximum NO, NO_2 and total NO_x emissions produced from neat RO and blend PRO7.5 as a function of engine speed (n)**

Analysis of the graphs in Fig. 2 shows, that the maximum NO_x emissions emanating from blend PRO7.5 fluctuate monotonously throughout the whole speed range sustaining at approximately from 25.3 % (1600 min^{-1}) to 17.4 % (2000 min^{-1}) higher levels than that of neat RO. The NO_x emissions higher up to 1805-1912 ppm have been obtained because of increased both by 25.2 % to 16.9 % NO and by 24 ppm or up to 2.8 times NO_2 emissions that can be attributed reasonably to rapid burning of combustible mixture prepared during the first stages of the process. Because RO differs as having higher start of vaporisation (299 ˚C) related to the diesel fuel (177.8 ˚C) and about same vaporisation end (345-346 °C) [8], mixing RO with lighter petrol extends evaporation temperature range from 35 to 195-210 ˚C that, on the one hand, may advance the start of vaporisation but, on the other hand, the lower cetane number of petrol may increase both auto-ignition delay and amount of fuel premixed for rapid combustion stimulating an increase in temperature related NO_x emissions.

The NO_2 emissions behaviour indicate that the burning process of blend PRO7.5 is complicated enough and proceeds, likely, with the presence of cooler regions, which are widespread across the combustion chamber and may quench the conversion back to NO [10], however the higher brake thermal efficiency 0.394 (RO) and 0.395 (PRO7.5) relative to that of 0.364 developed by the fully loaded engine run on blend ERO7.5 at rated 2200 min^{-1} speed [1] shows real advantages of petrol as potential agent to be used for rapeseed oil treatment. It is worth to notice, that the NO_2/NO_x ratios in the case of fuelling the engine with blend PRO7.5 change from 1.32 times (1400 min^{-1}) lower to 2.38 times (2200 min^{-1}) higher relative to that of neat RO, i.e., have been significantly reduced comparing with those generated at corresponding loading conditions from blend ERO7.5 [5].

Carbon monoxide CO emissions depend on the engine load, speed and quantity of petrol added in the RO. Starting at light load, λ=6.0, and low 1400 min^{-1} speed from comparably high 332 ppm (RO) and 1576 ppm (PRO7.5) levels, they vary to 350 and 584 ppm for medium loads and increase again up to 922 and 779 ppm, correspondingly, for heavy loading conditions.

In the case of running the fully loaded engine, λ=1.6, on blend PRO7.5, CO emissions are lower by 15.5 % relative to that of neat RO at low 1400 min^{-1} speed and scale up in speed increasing order by 8.8 %, 47.2 %, 31.8 % and 33.4 %, respectively, during transition to rated 2200 min^{-1} speed (Fig. 3). Considerably (by 57.6 %) diminished smoke opacity and lower CO emissions emanating from the fully loaded engine operating at low 1400 min^{-1} speed can be attributed to improved kinematical viscosity, better atomization of fuel spray patterns and higher calorific value of blend PRO7.5 whereas certain increase of CO emissions with revolutions can be associated with lower cetane number of petrol and correlates reasonably well with higher both NO_2 and NO_2/NO_x emissions (Fig. 2).

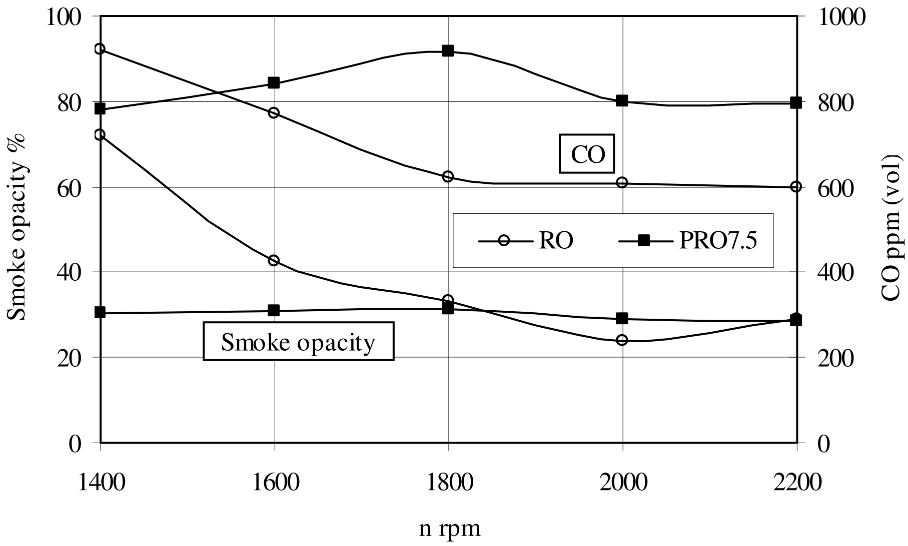

Fig. 3. **Dependencies of CO emissions and smoke opacity of the exhausts on engine speed (*n*) when operating under heavy loading conditions, λ = 1.6**

It is important to notice, that in contrast to the test results obtained in the previous research [5], where visible smoke from the fully loaded engine operating on blend ERO7.5 (12.6 % oxygen) was higher by 55.5 % at low 1400 min^{-1} speed, in the case of fuelling it with blend PRO7.5 (10.0 % oxygen) the smoke opacity is significantly reduced and it does not change actually with revolutions sustaining throughout the whole speed 1400-2200 min^{-1} range at low 30.5-28.3 % level. The base-line smoke opacity measured from the fully loaded engine run on neat RO (10.8 % oxygen) diminishes gradually with revolutions from 72.0 % to 29 % for rated 2200 min^{-1} speed because of increased fuel injection pressure, better atomization of viscous and heavy oil droplets and intensified mixing by cylinder air swirl. Considerable reduction of smoke opacity, achieved due to fuelling the diesel engine with more calorific blend PRO7.5, correlates pretty well with better engine performance efficiency [1] and higher NO and NO_x emissions [2] as unavoidable penalty (Fig. 2).

Emissions of unburned hydrocarbons HC emanating from ERO and PRO blends are negligibly small, 2-16 ppm, and increase gradually with load (bmep) and the portion of fuel injected. When running the fully loaded engine, λ=1.6, at rated 2200 min^{-1} speed, HC emissions from blend PRO7.5 are higher by 9-11 ppm relative to that of neat RO. Reasonably higher HC emissions from oxygenated blends tested have been measured for all loading conditions and rotation speeds because the presence of lighter fuel additives such as ethanol and petrol may increase their penetration deeper into the combustion chamber cavities where the flame-quenching effect usually occurs [10]. In the case of running the fully loaded engine on blend PRO7.5 at rated 2200 min^{-1} speed, carbon dioxide CO_2 emissions were reduced from 7.8 vol % to 7.6 vol % and temperature of the exhausts was increased from 500 to 512 ˚C remaining in good harmony with lower smoke opacity of the exhausts.

Conclusions

1. The test results indicate that when running of the fully loaded engine D-243 under constant air-to-fuel equivalence ratio, λ=1.6, at the maximum torque 1800 min^{-1} and rated 2200 min^{-1} speed blend PRO7.5 ensures the brake mean effective pressure lower by 2.6 % (*bmep*=0.750 MPa) and 0.5 % (*bmep*=0.736 MPa) than that of neat RO. In the case of fuelling the diesel engine with blend PRO7.5, the brake specific energy consumption (bsec) in MJ/kWh for light, medium and heavy loads is higher by 15.9 %, 8.9 % and 5.3 % at low 1400 min^{-1} speed whereas during engine operation with the fully opened throttle at maximum torque 1800 min^{-1} and rated 2200 min^{-1} speed, the bsec is correspondingly higher by 2.1 % and lower by 0.7 % relative to that of neat RO (9.21 and 9.14 MJ/kg).
2. 2. The maximum NO and NO_x emissions emanating from blend PRO7.5 are higher by 25.2 % to 16.9 % and by 25.3 % to 17.4 % at 1600 min^{-1} and 2000 min^{-1} speeds and NO_2 emissions higher by up to 24 ppm comparing with that of neat RO. Higher NO and NO_x emissions generated by more calorific blend PRO7.5 can be attributed reasonably to higher cylinder gas temperature whereas slightly increased NO_2 emission indicates that the combustion process of petrol treated RO proceeds, likely, with the presence of cooler regions, which may quench the conversion back to NO.
3. 3. Carbon monoxide, CO, emissions and smoke opacity from the fully loaded engine operating on blend PRO7.5 suspend at 779 ppm and 30.5 % levels that is lower by 15.5 % and 57.6 % at low 1400 min^{-1} speed whereas after transition to rated 2200 min^{-1} speed, CO emissions increase by 200 ppm or 33.4 % and smoke opacity remains at lower by 2.4 % level (28.3 %) relative to that of neat rapeseed oil (29.0 %). Emissions of unburned hydrocarbons HC generated from blend PRO7.5 are higher by up to 9-11 ppm relative to that of neat RO along with CO_2 emissions diminished from 7.8 vol % to 7.6 vo l% and temperature of the exhausts increased from 500 to 512 °C at rated 2200 min^{-1} speed.

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