Reducing Pollutants from Mobile Sources

FINAL REPORT

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Abstract

Results of experimental investigations of using a coil-shaped injector for reducing NOx emissions from a diesel engine are presented. The study involved the effects of coil length and its mixing effectiveness and the development of the injector system for after treatment of diesel exhausts.

Results indicate that the coil-shaped injector system with the ratios of length, pitch and wire diameter to the exhaust pipe diameter, L/D, p/D, d/D, of respectively 1.25, 1.0, and 0.13 can reduce the NOx emissions of the diesel engine by more than 10% when diesel oil is used as the treatment agent.

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Disclosure

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1.0. INTRODUCTION

It has been well established that if oxides of nitrogen (NOx) and air are irradiated with ultra violet light, the net effect is a dynamic equilibrium with ozone being one of its products. However, if a hydrocarbon is also present, the reduction is unbalanced and the net effect is the production of nitrogen dioxide and ozone. The effects of ozone on the environment are well known and every effort should be made to reduce ozone's formation in the earth's atmosphere.

The quantities of NOx emissions vary with flame temperature, excess air or excess oxygen, and combustion residence time. Effective control of NOx emissions requires the application of one or a combination of methods of combustion process modifications including staged air injection, and post combustion after treatment. Reviews of various emission control measures are provided by Heimrich [1] and Modt [2].

The current federal emissions standards limits for heavy duty on-road diesel engines (> 8,500 lbs) are 4.0 g/bhp-hr of nitrogen oxide, NOx, 0.1 g/bhp-hr of particulate matter, PM, and 1.3 g/bhp-hr of non-methane hydrocarbons, NMHC. To reduce the overall exhaust pollution, three-way catalytic converters (Kummer [3]) have been used in vehicle exhaust system to oxidize or burn the Hydrocarbons (HC) and Carbon Monoxide (CO) gases after they leave the engine. They are usually placed in the exhaust system ahead of the muffler and close to the exhaust manifold where temperature of the exhaust gases is high. These converters are of two types; monolith and pellet. The monolith converter has special honeycomb made of ceramic material, which is coated with platinum and palladium, to oxidize the gases. The pallet converter has aluminum oxide pallets inside a stainless steel shell for oxidation process. These converters are efficient at high temperatures and reduce HC and CO emissions substantially.

The function of a three-way catalyst depends on the combustion process. For the catalyst to work properly, the combustion process should be nearly stoichometric . If the exhaust is too lean, NOx are not destroyed and if it is too rich HC and CO are not removed. For a diesel engine, reduction of NOx is very limited due to the fact that diesel engines run lean. Thus, reduction of NOx emissions is performed with design of combustion process and/or the choice of operating conditions. The introduction of selective catalytic reduction (SCR) systems using urea as the removing agent has shown to be effective in reducing NOx emissions in diesel engines. Urea is produced by combining ammonia and carbon dioxide at high pressure. When it is injected into the exhaust of a diesel engine, it first hydrolyzed to produce ammonia and then ammonia will react with the exhaust gases to produce nitrogen and water. Fable et al [4] provide a comprehensive study of urea infrastructure required for SCR technology to meet the current and future federal emissions standards for heavy duty diesel on-road engines.

To further reduce these emissions, new methods such as exhaust gas recirculation (EGR) is being tested by the diesel engine manufacturer. In EGR approach, the exhaust gas acts as diluents in the air-fuel mixture to lower the combustion rate and temperature, thus increase its efficiency and reduce NOx emissions. The maximum EGR fraction is 15-20% of the fuel-air flow rate which limits its capability for a high rate of reduction in emissions. Thus, multi-methods should be implemented to drastically reduce diesel exhaust emissions.

Reduction of NOx emission can also be accomplished with a SCR system with fuel as the reducing agent. The system can use the on board fuel tank as its reservoir and a control system can be used to time the injection process to the engine timing to optimize the NOx reduction process. The byproduct is nitrogen, carbon dioxide and water. The post combustion aftertreatment is the method used for the present investigation, using a coil-shaped injector system and the diesel fuel as the reducing agent.

The role of streamwise vortices on mixing and entrainment of a round jet have been extensively investigated by many researchers (Ex. Yule[5], Liepmann[6], Liepmann and Gharib[7] }. In the near field transition region, experimental investigations of Liepmann6] and Liepmann and Gharib[7] have shown the development of streamwise vortex pair (Bernel-Roshko structures) in the braid region between primary vortical structures, which significantly affects the near field entrainment process. Additional mixing enhancement can be obtained with vortex generators. Previous studies (i.e. Bradbury and Khadem[8], Samimy et al[9], Zaman et al[10]) have shown that square thin plates placed inside a jet at the outlet at different angles; generate trailing vortex motions, which enhance the mixing process. In a mixing layer, Bell and Mehta[11] have shown that the introduction of spanwise perturbations at the origin of a mixing layer results in generation of regular arrays of counter rotating vortices which increases the mixing growth rate in the near field.

The objectives of the present study were experimental investigations of the following tasks:

1) the effect of various coil lengths with the optimized pitch and wire diameter on mixing enhancement of a turbulent jet and on pressure drop inside a tube,

2) mixing effectiveness of a heated optimized coil, and

3) the effect of a an optimized coil-shaped oxidizer injector on the emission of a diesel engine.

2.0. BACKGROUND

Relevant to the present study are results of extensive investigations of flow characteristics in the interior of the fluted tube presented by Yampolsky et. al. [12], Yang et. al. [13], and Babikian et al [14]. Results of Yampolsky et al [12] and Yang et al [13] indicate that the spiral flutes along the interior of the tube lead to an increase in the heat transfer coefficient by a factor of two to three, with a modest or negligible increase in the pressure drop as compared to a tube with a smooth surface.

Results of Babikian et al [14] show that the presence of the flutes induce a mean swirl on the flow field which transfers turbulent kinetic energy from the radial to the axial component. The azimuthal turbulent velocity component is reduced while at some radial locations; the axial turbulent velocity is increased.

Rahai and Wong [15] presented results of experimental studies of the effects of coils of constant wire diameter but different pitch spacing on a turbulent jet. In their study, the ratios of coils pitch spacing to the tube inside diameter, p/D, are 0.4, 0.7, 1.2, and 2.7 and the ratio of coils wire diameter to the tube inside diameter, d/D, is 0.027. Experiments are performed at five axial locations up to 10 orifice diameters. Results show that the coils with large pitch spacing cause significant decrease in the maximum mean velocity and increase in the jet half width and turbulent velocities in the jet developing region which are indications of higher mixing process with the surrounding air. These effects are more pronounced when $\frac{p}{D}$=1.2. Rahai and Hoang [16] extended these studies to a coil with $\frac{p}{D}$=1.2 and d/D = 0.17. Their results show that increasing the wire diameter results in higher swirl, and higher turbulent kinetic energy and jet half-width and thus higher mixing process. The swirl causes generation of tangential turbulent shear stress and reduction in the radial turbulent shear stress.
For all our previous investigations on coil-inserted jet, the coil insert length was 28.6 cm (L/D=22.5). In the present investigation the effect of coil length on pressure drop and mixing enhancement inside a tube has also been investigated.

One important result of the present investigation is an optimized coil configuration which can be used for development of a new catalytic converter for NOx reduction. The mixing effectiveness of the optimized coil is an indication of increased contact between the exhaust gases and the coil and if the principle metal for the coil is Rhodium, then it can acts as a catalyst for NOx reduction.

3.0. EXPERIMENTAL PROCEDURE AND TECHNIQUES

The central tube of the main combustion unit of the combustion laboratory in the Mechanical and Aerospace Engineering (MAE) Department at California State University, Long Beach (CSULB) was used for investigation of the mixing effectiveness of the coil insert with various lengths. Details of the experimental set-up are given by Rahai and Wong [15] and Hoang and Rahai [16].

Five coils with p/D=1.2 and d/D=0.06 with approximate lengths of 28.6, 14.3, 7.16, 3.6, 1.81 cm were used in the experiments. The ratios of the coil length to the tube inside diameter, L/D, were 22.6, 11.26, 5.64, 2.82, and 1.41. The coils were inserted in the central tube, terminating at the jet outlet.

Filtered laboratory air, supplied at a steady rate was sent through the tube. The supplied airflow rate was kept at a constant rate of 5.66 $\frac{m^3}{hr}$. The Reynolds number based on the tube inside diameter and the volume flow rate was 10,187. Measurements were carried out at six streamwise locations of X/D = 0.1, 1.0, 3.0, 5.0, 10, and 15, and various radial locations across the jet using a TSI double sensor hot wire probe model 1243-T1.5 connected to two channels of TSI IFA-100 intelligent flow analyzer. Measurements were carried out twice to obtain the three components of the turbulent velocity. At each measurement location 50 records where each record contains 2048 samples of data were digitized at a sample rate of 6000 samples/sec., using a Metra-Byte DAS-20 Analog to digital converter. Digitized data were analyzed using software supplied by Data Ready, Inc.

To investigate the pressure drop due to coils of various lengths, an open axi-symmetric jet connected to compressed air was used. Figure 1 shows the experimental set-up.

Figure 1. The open jet facility.

The air enters a round settling chamber of 30.5 cm diameter and impinges on a small flat plate to fill the chamber. The settling chamber is 132 cm length and has various screens with different solidity for flow conditioning. The settling chamber is followed by a 11.75:1 contraction, which is 26.7 cm long. A second axi-symmetric contraction with an area ratio of 12.25:1 and length of 10.16 cm followed the first contraction with a round exit inside diameter of 2.54 cm. A small round enlarged tube was attached to the outlet of this contraction for attachment of various tubes with 2.54 cm ID. This tube is placed at the mid section of a large all Plexiglas facility with an intake honeycomb plane to prevent any distortion from outside air.

PVC round tube of 2.54 cm ID and 66 cm in length was attached to the outlet of the jet (Figure 2). The tube had two pressure taps with an approximately 33 cm tube length in between. The distance between the jet outlet and the first pressure port was 16.51 cm.

Three coils with p/D = 1., d/D = 0.1 and L/D = 10.5, 5.625, and 1.25 (Figure 2) were inserted into the tube between the pressure taps, one at a time and pressure drop across the smooth and the coil-inserted tubes were measured using a Setra system pressure transducer model 239. The same computer facility as in the hot wire measurements was used to record the pressure differential across the tube and also the jet mean velocity for different Reynolds numbers. For each measurement, five records where each record contains 1024 samples were digitized at a sample rate of 2048 samples per channel. The results were analyzed using a modified software supplied by Data Ready Inc.

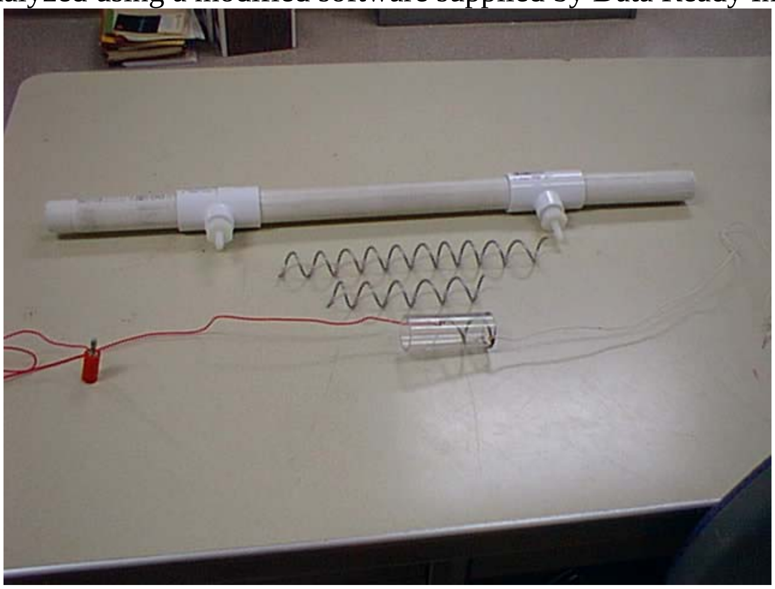


Figure 2. The round tube for pressure drop measurement and the coil inserts.

For task 2, only the coil with L/D = 1.25 was heated. The coil was inserted into a Plexiglas tube of 2.54 cm diameter and 5.08 cm in length. DC voltage was supplied to the coil to increase the temperature of the heated jet by approximately 0.7 C. The experiments were carried out at a mean velocity of 6.82 m/sec which corresponds to an approximate Reynolds number based on inside diameter of 11,176.

Mean temperature measurements across the jet in both spanwise and vertical directions along the jet mid section were performed using a fast response calibrated RTD probe connected to the same data acquisition facility used for the pressure measurements.

Two configurations of coil terminating at the tube outlet or placed at the outlet of jet inside the tube were investigated. For the first configuration both spanwise and vertical mean temperature measurements were performed. For the second configuration, only the vertical measurements were performed.

For emission test, the single cylinder diesel engine in the MAE Department at CSULB was used. The engine is mounted on an electric dynamometer, which can measures the output torque at the shaft. Various installed thermocouples provide the temperatures of inlet and outlet cooling water, inlet air and exhaust gas. Various ports in the exhaust pipe are provided for emission measurements at different locations.

Figure 3 shows the injection unit attached to the exhaust pipe of the diesel engine. The stainless steel unit has a copper coil-shaped tube injector inside right at the unit inlet. The coil has a p/D = 1.0, d/D= 0.135 and L/D=1.25. Various circular holes at 0.08mm diameter were imbedded in the tube for injection purposes. The configurations of the holes were such that the injected treatment fluid was mixed effectively with the exhaust gas.

The coiled tube was connected to a Filter-Regulator-Lubricator (FRL) combination with compressed air as input. The lubricator had diesel fuel and could maintain a constant air-oil ratio, regardless of changes in air flow. The flow capacity was 44 SCFM (0.02 m^3/sec) and useful retention was 18 cm^3.

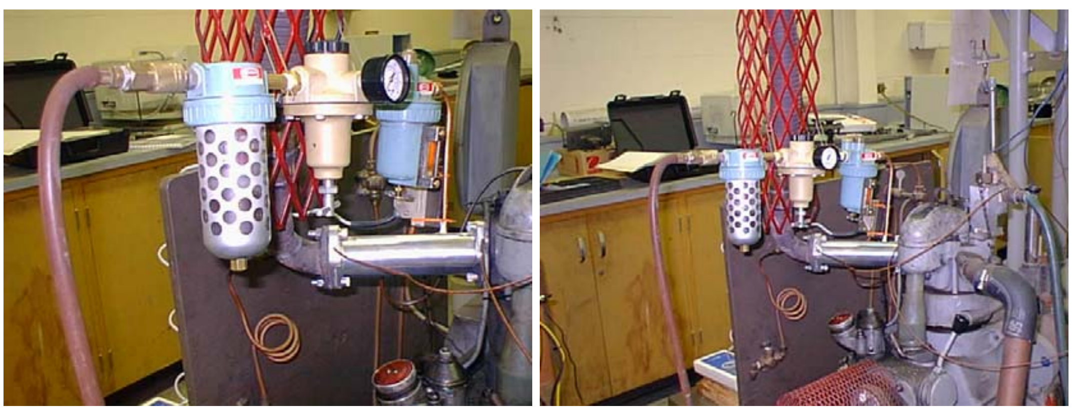


Figure 3. Diesel engine and the exhaust aftertreatment system.

Emission measurements were performed using an ENERAC Micro-Emissions Analyzer Model 500 with the associated probe. It measures ambient and stack temperatures (0-1100 C, 1 degree resolution), Oxygen (Electrochemical cell, 0-25%, 0.1% resolution), NO (Electrochemical cell, 0-2000PPM, 1 PPM resolution), NO2 (Electrochemical cell, 0-1000PPM, 1 PPM resolution), CO (Electrochemical cell, 0-2000 PPM, 1 PPM resolution), SO2 (Electrochemical cell, 0-2000 PPM, 1 PPM resolution), Combustibles (Catalytic sensor, 0-5% range, 0.1% resolution), and Stack Draft (Piezoresistive sensor, 10 to –40” WC range, 0.1” WC resolution). It can measure emissions from 15 fuels including diesel oil, and 11 gases including Ammonia and Ethylene.

4.0. RESULTS AND DISCUSSIONS

Task 1.

Figures 4 and 5 show radial variations of the normalized axial mean velocity, and turbulent kinetic energy, TKE, at X/D = 0.1 and 3. At X/D = 0.1 the mean velocity profiles for all jets are nearly Gaussian and the results for the coil inserted tubes show increased radial expansions. The profiles for the tubes with L/D = 2.82 and 1.41 are shifted to the right which is due to the coils positioning and the way they terminate at the tubes outlets.

As compared to the corresponding values for the smooth tube there are increases in the turbulent kinetic energy for the coil inserted tubes at the shear layers with larger increases for the tubes with L/D = 11.26 and 22.5.

At X/D =3, while the mean velocity profiles are all Gaussian, there are further radial expansions in the mean velocity profiles for the coil inserted tubes and the shifts in the mean velocity profiles of the tubes with L/D = 2.82 and 1.41 are more pronounced. There are large increases in the TKE for the coil inserted tubes and results indicate that for the coil inserted tubes with L/D = 1.26 and 5.64, the dip along the jet centerline has disappeared.

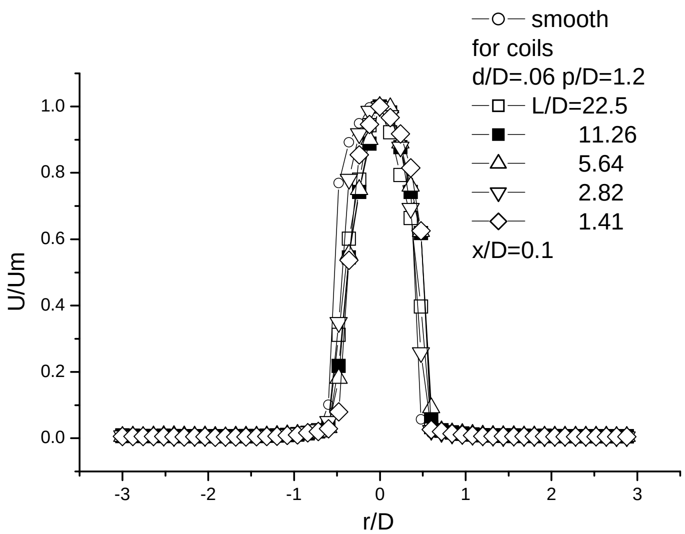
Figure 6 shows axial variations of the maximum mean velocity, jets half width and turbulence intensity along the jets centerlines. There are large decreases in the maximum mean velocity for the coil-inserted tubes. At X/D = 1, the largest decrease is for the tubes with L/D =11.26 and 22.5. However, at further downstream locations, the maximum mean velocity for the tube with L/D = 5.64 is decreased significantly and becomes less than the corresponding values for all other tubes at X/D = 3 and 5. At X/D = 10 and 15, the decay rate for the coil-inserted tube with L/D = 2.82 is higher than the corresponding decay rates for all the other tubes.

The decreases in the maximum mean velocity corresponds to increases in the jets half widths with the highest increase being for the coil inserted tube with L/D = 2.86 at X/D>5.

The decrease and increase in the maximum mean velocity and jets half-width are indications of high rate of entrainment and mixing process for the jets. The increase in the rate of entrainment and mixing are also associated with large increases in the centerline turbulence intensity.

Figure 7 shows smoke flow visualization of a smooth and a coil inserted tube with L/D=11.26 at the same Reynolds number that the experiments were performed. As the pictures show, the coil inserted tube has much higher mixing process in the near field region than the smooth tube and there are indications of added streamwise vortices generated by the coil which should be responsible for this enhanced mixing process.

From these results it can be conjectured that the coil inserts with d/D< 0.1 generate streamwise vortices at the jet outlet that enhance the mixing process in an axi-symmetric jet. These streamwise vortices maybe as a results of upstream “pressure hills”, as explained by Zaman et al [10] with positive and negative sense of rotation (depending on the location), expanding the jet in the radial direction with high rate of entrainment and mixing process. Reducing the coil length will delay the effects of these vortices and the mixing enhancement to a further downstream location.



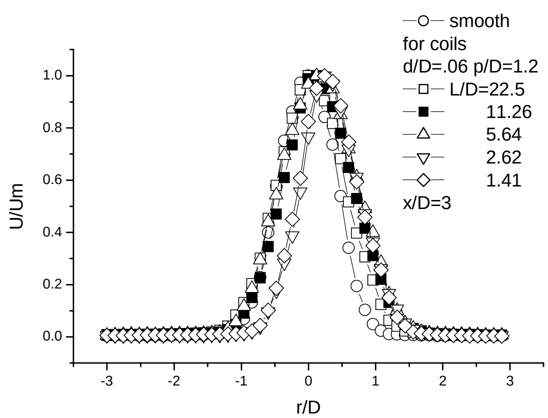


Figure 4. Radial variations of normalized axial mean velocity at X/D = 0.1 and 3.

Uncertainty in $\frac{U}{U_0}$ is ± 0.005, in $\frac{r}{D}$ is ± 0.05 , and in X/D is ± 0.05 at 20:1 odd.

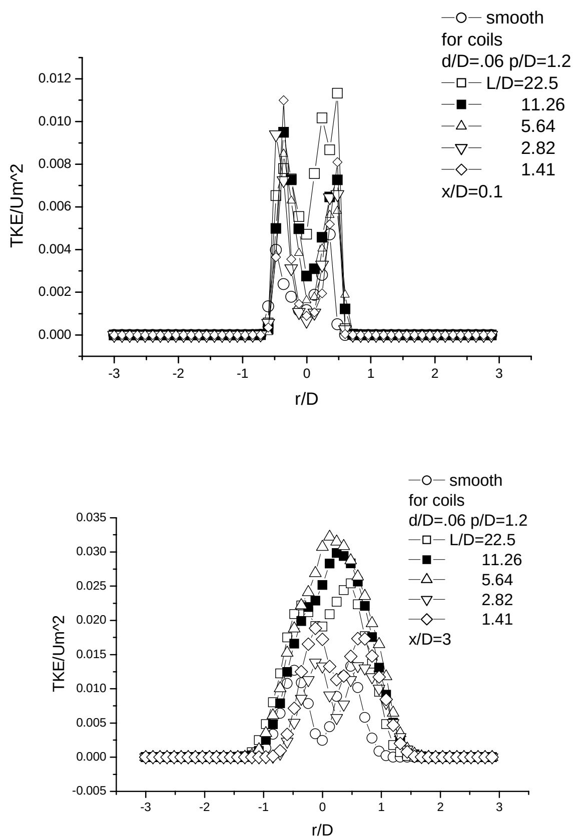


Figure 5. Radial variations of normalized TKE at X/D = 0.1 and 3. Uncertainty in TKE is ± 0.0004 and in $\frac{r}{D}$ and X/D are the same as in Fig. 5.

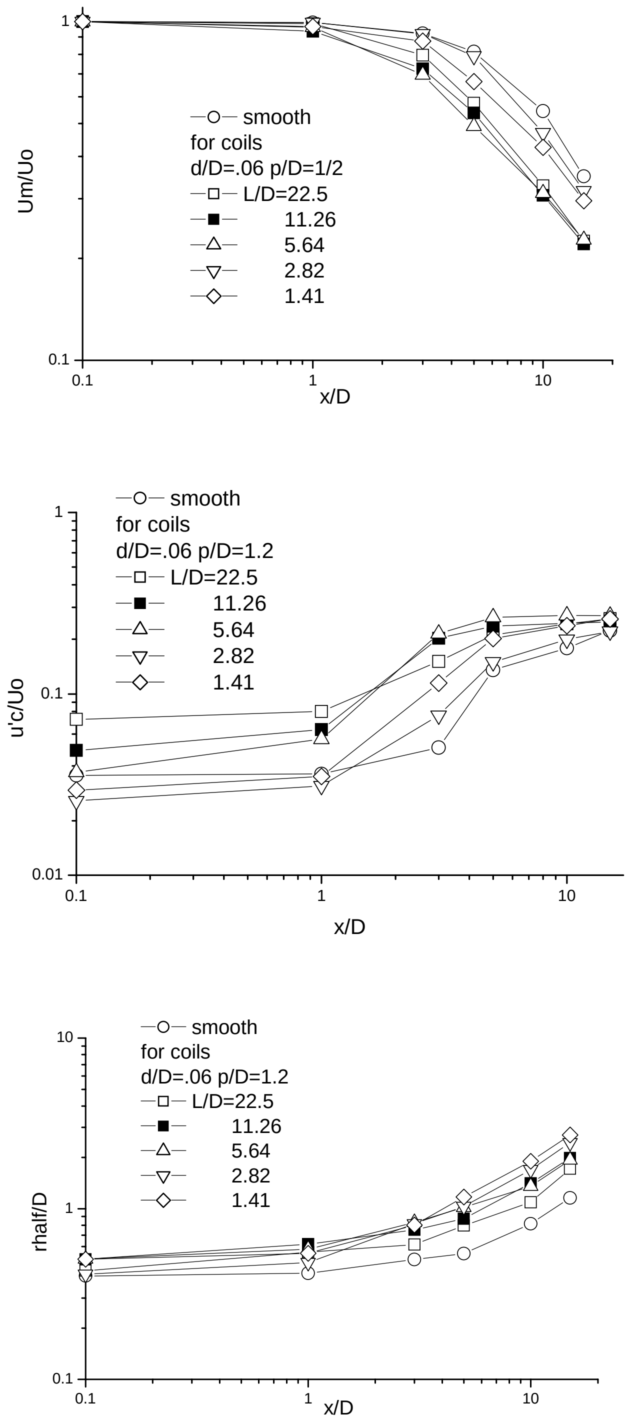


Figure 6. Axial decays of the flow center mean velocity and axial turbulence intensity and axial variation of the jet half widths. Uncertainty in rhaf is ± 0.05, in $\frac{U_m}{U_0}$ is ± 0.005 , and in u'_c/U_0 is ± 0.02 at 20:1 odd.

(a)

(b)

Figure 7. Smoke flow visualization, (a) smooth tube, (b) coil inserted tube with d/D=0.06, p/D =1.2 and L/D = 11.26.

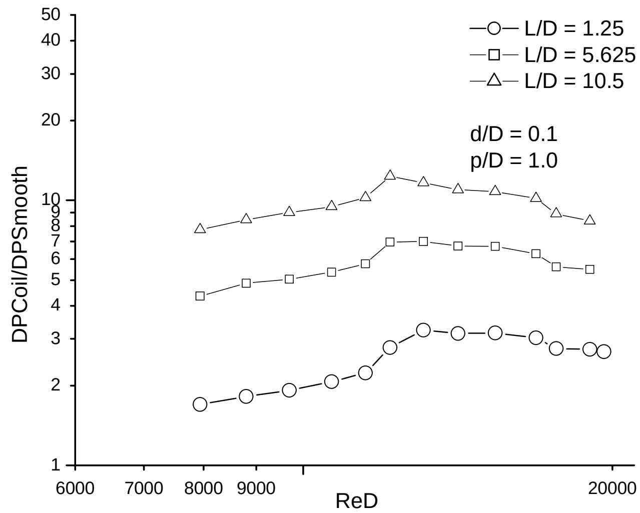


Figure 8. Variation of normalized pressure drop with Reynolds number.

Figure 9 shows variation of normalized pressure drop with Reynolds number for three coils with various lengths, but constant diameter and pitch spacing. As the results show, initially the pressure drop increases with Reynolds number, until a Reynolds number of about 11,000, where it starts to decrease. The increase in length increases the pressure drop and the lowest drop is for the coil with L/D = 1.25.

For a full size eighteen wheel diesel truck, the exhaust Reynolds number is much higher than the maximum Reynolds number investigated, and for this high Reynolds number, the pressure drop should approach a constant value. For the single cylinder diesel engine investigated, the Reynolds number is very low and the normalized pressure drop for the coil with L/D = 1.25 should be near one. Thus, this configuration was used to investigate the mixing effectiveness of the heated coil as identified in task 2.

Task 2.

Figure 10 shows variation of normalized temperature across the jet for a heated coil. Due to the asymmetric configuration of the coil, measurements were performed in both vertical and spanwise directions. In addition, the effects of both inlet and outlet locations on the mixing process were investigated.

Results show that maximum variation in the temperature is in vertical direction, which is slightly higher than 3%. When the coil is placed at the inlet of the tube, maximum variation in temperature is decreased to about 1.5% indicating enhanced mixing process within the tube. These results indicate that the heated coil with this configuration is an effective mixing device, which can be used for development of the injector system for aftertreamnet of the exhaust gases.

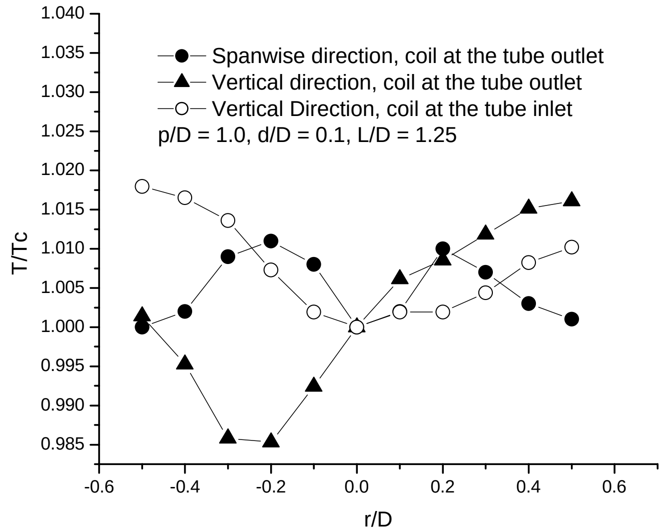


Figure 9. Variation of normalized temperature across the jet with heated coil.

Task 3.

Preliminary test of the injection system was performed using diesel oil (no. 2) as the after treatment agent. The test was performed both with and without the aftertreatment. For both conditions, the engine speed was at 800 rpm and the BHP was at 0.8 and the exhaust temperature measured both at the inlet and outlet of the injector tube was about 152 C. When aftertreatment was used, the air pressure was set at 12 PSI.

Results showed that as the mixture of air and fuel was injected into the exhaust, the NOx emission was reduced by more than 10% while the excess air was increased by nearly 25%.

5.0. CONCLUSIONS AND RECOMMENDATIONS

The effects of coil inserts with constant pitch spacing and wire diameter of p/D = 1.2 and d/D= 0.06 and various lengths of L/D = 22.6, 11.26, 5.64, 2.82, and 1.41, on mixing enhancement of a round turbulent jet were experimentally investigated. Results indicated that the coil inserts enhance the mixing process in the near field of a round jet. At the tube outlet, the largest mixing was obtained when L/D = 11.26 and 22.6. However, at further downstream locations, the largest mixing was associated with the coil-inserted tube with L/D = 1.41. These results indicate that large mixing could be obtained with a coil with small L/D ratio and reducing coil length would delay the mixing enhancement to a further downstream location.

The results of pressure measurements inside a coil inserted tube indicated that, reducing the length decreases the pressure drop across the coil and at very low Reynolds numbers, the increase in the pressure drop is not significant and at very high Reynolds numbers, it is nearly a constant value. Results of temperature measurements indicated that the heated coil is a good mixing device. Emission measurements using the coil-shaped injector with diesel as the post treatment agent showed more than 10% reduction in NOx emission for the limited measurements performed. Further reduction in NOx emission is possible with timing control of engine combustion and the injection process.

Further emission tests are planned with different agents such as Ammonia and Ethylene and results will be presented in the near future. Further exploration of using the present configuration for development of a Rhodium catalyst-injector system for NOx reduction in diesel engines is recommended. A Rhodium catalyst-injector system along with an EGR system can reduce diesel engine emissions by more than half, to meet the new approved federal emissions standards for heavy duty on road diesel engines.

REFERENCES

1. Heimrich, M.J., 1996, “Diesel NOx Catalytic Converter Development: A Review,” J. of Engineering for Gas Turbines and Power, Transactions of ASME, Vol. 118, pp. 668-672.

2. Mondt, J.R., 2000, “Clean Cars: The History and Technology of Emission Control Since the 1960s,” SAE International, Warrendale, Pennsylvania.

3. Kummer, J., 1981, “Catalysts for Automobile Emission Contro,” Prog. Energy Combust. Sci., Vol. 6, pp. 177-199.

4. Fable, S., Kamakate, F., and Venkatesh, S., 2002, “Selective Catalytic Reduction Urea Inferastructure Study,” National Renewable Energy Laboratory, NREL/SR-540-32689.

5. Yule, A. J., 1978, “ Large Scale Structure in the Mixing layer of a Round jet,“ J. Fluid Mech. 89, 413.

6. Liepman, D., 1991, “Streamwise Vorticity and Entrainment in the Near Field of a Round Jet,” Phys. Fluids A 3, 1179-1187.

7. Liepman, D. and Gharib, M., 1992, “ The role of Streamwise Vorticity in the Near-Field Entrainment of Round Jets,” J. Fluid Mech., 245, 643-668.

8. Bradbury, L.J.S., and Khadem, A.H., 1975, “The Distortion of a Jet by Tabs,” J. Fluid Mech. Vol. 70, 801.

9. Samimy, M., Zaman, K.B.M.Q., and Reeder, M.F., 1993, “Effect of Tabs at the Nozzle Lip on the Flow and Noise Field of an Axisymmetric Jet, “ AIAA J., 31, 609.

10. Zaman, K.B.M.Q., Samimy, M., and Reeder, M.F., 1994, “Control of an Axisymmetric Jet Using Vortex Generator,” Phys. Fluids, 6 (2), 778-793.

11. Bell, J. H., and Mehta, R. D., 1993, “Effects of Imposed Spanwise Perturbations on Plane Mixing-Layer Structure,” J. Fluid Mech., 257, 33-63.

12. Yamplosky, J.S., Libby, P.A., Launder, B.E. and LaRue, J.C., ``Fluid Mechanics and Heat Transfer of Spiral Fluted Tubing," GA Technologies Report GA-A17833, 1984.

13. Yang, S.R., Zai, G.D. and Kim, R.H., ``Experimental Investigation of a Spiral Turbulator with a Reinforcing Wire As an Augmentator/Cleaner in the Tube Side of Surface Condensers," Proceeding of CSME Mechanical Engineering Forum 1990, University of Toronto, June 3-9, 1990.

14 Babikian, D.S., LaRue, J.C., and Rahai, H.R., ``Characteristics of the Velocity Field in the Central Region of a Spirally Fluted Tube, "Paper No. III-3, Proceeding of the Eight Symposium on Turbulent Shear Flows, September 9-11, 1991, Munich, Germany.

15. Rahai, H.R., and Wong, T.W.,2002, "Velocity Field Characteristics of Turbulent Jets From Round Tubes with Coil Inserts," Appl. Therm. Eng., 22, 1037-1045.

16. Hoang, H. T., and Rahai, H. R., 2002, "The Distortion of a jet by Coil Inserts," ASME J. Fluids Eng., 124, June, 500-505.

APPENDIX

NOMENCLATURE

D = tube inside diameter, cm

DP = pressure drop, inch H2O

T = temperature, C

Tc = centerline temperature, C

U = axial mean velocity, m/s

U_m = maximum mean velocity, m/s

U_O = maximum mean velocity at X/D = 0.1, tube outlet, m/s

u'_c = rms axial turbulent velocity along the centerline

$\overline{u^2}$ = mean squared axial turbulent velocity, $\frac{m^2}{s^2}$

$\overline{v^2}$ = mean squared radial turbulent velocity, $\frac{m^2}{s^2}$

$\overline{w^2}$ = mean squared tangential turbulent velocity, $\frac{m^2}{s^2}$

L = coil length, cm

X = axial distance, cm

d = coil wire diameter, mm

p = pitch spacing, mm

r = radial distance, cm

rhalf = jet half width, cm

TKE= turbulent kinetic energy, $\frac{m^2}{s^2}$ = ½ ($\overline{u^2}$ + $\overline{v^2}$ + $\overline{w^2}$)