Testing of a Volatile Particle Remover (VPR) and a Thermo-Denuder (TD) Using a DISI Engine

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1. Introduction

The emissions of fine particles have been shown to have a large impact on the atmospheric environment and human health. Researchers have shown that gasoline engines, especially Direct Injection Spark Ignition (DISI) engines, tend to emit large amounts of small size particles compared to diesel engines fitted with Diesel Particulate Filters (DPFs). As a result, the particle number emissions of DISI engines will be restricted by the forthcoming EU6 legislation.

To investigate the characteristics of particle emissions from engines, a Catalytic Stripper (CS, an oxidation catalyst) has been tested by Kittelson and co-workers [1,2]. It was reported that complete removal of volatile particles could be achieved but that it also led to the removal of 15-25% of the solid particles. This loss has been attributed to thermophoretic deposition caused by cooling after the catalytic stripper. A Volatile Particle Remover (VPR) system is required by the European PMP programme [3,4]. The particle loss in the catalytic stripper led to the development of a Solid Particle Sampling System (SPSS) [5] that used dilution immediately after an oxidation catalyst. Khalek [5] presents a comprehensive discussion and analysis of the operation of the SPSS, and characterises its performance using salt (NaCl), ammonium sulfate and oil aerosols. The ammonium sulphate decomposed and (as with the oil) led to particle penetration through the SPSS that was always below 10%. In contrast the penetration of the salt aerosol was, within experimental tolerance, 100%. In a subsequent paper Khalek and Bougher [6] compare the performance of the SPSS using a Catalytic Stripper (CS, an oxidation catalyst) with an Evaporation Tube (ET) using particles of tetracontane (as specified in the European PMP). They conclude that the Catalytic Stripper outperforms the Evaporation Tube, since the catalytic stripper will oxidise the vaporised hydrocarbons so that there is then no possibility of their re-condensation. So, it is of interest to investigate the performance of the Catalytic Stripper based Volatile Particle Remover System on the PM emissions from a SGDI (Spray Guided Direct Injection) engine; previous work has utilised a wall guided direct injection engine [7]. In the work reported here, engine experiments were carried out to study a Catalytic Volatile Particle Remover (VPR) and a Thermo-Denuder (TD), and to find out if they can achieve the transmission efficiencies required by the PMP procedures.

2. Experimental Setup

The test engine was a Jaguar naturally aspirated, V8 direct injection spark ignition engine [8]. The test conditions for VPR and TD tests are listed in Table 1. Schematics of the particulate emissions measurement system for the VPR and TD tests are shown in Fig. 1.

It can be seen from Fig. 1 that in VPR Test 1, the exhaust Pre-TWC was drawn into the Catalytic VPR. At each test point, the PM emissions Pre-VPR and Post-VPR were measured using a Cambustion DMS500 particle sizer [9]. The sampling flow rate of the DMS (MFM_{DMS}) was set to 0.02 g/s. A pneumatic switching valve was used to select between Pre-VPR and Post-VPR. The switching valve was heated by hot air to keep the sampling temperature at around 90^{o}C, thereby preventing particle formation by condensation. The temperature of the sample flow pre and post VPR, as well as the flow temperature entering DMS, were measured using thermocouples. Downstream of

the Catalytic VPR, the exhaust flow then entered a dilution/extraction system. As a result, the residence time of the exhaust gas in the Catalytic VPR was varied, and the effects of exhaust residence time on PM emissions were studied by means of varying the flow rate of the dilution gas (MFM_{air}) added upstream of the VPR. Also, in this test, the VPR temperature was changed to investigate its effect on the VPR performance. The test conditions are listed in Table 2. The residence time (t_r) is calculated assuming a linear variation in the temperature within the Catalytic VPR along its length.

$$\dot{V} = \frac{\dot{m} \times R_s \times (T_1 + T_2)/2}{P} \quad (1)$$

$$t_r = V/\dot{V} \quad (2)$$

where $\dot{V}$ (m^3/s) represents the volume flow rate through the VPR, $\dot{m}$ (g/s) represents the mass flow rate through VPR, R_s ($J \times g^{-1} \times K^{-1}$) represents the specific gas constant of exhaust, T_1 (K) represents the pre-VPR temperature, T_2 (K) represents the Post-VPR temperature, P (Pa) represents the exhaust pressure, t_r (s) represents the residence time, V (m^3) represents the internal volume of the Catalytic VPR.

In Test 2, the exhaust was sampled downstream of the TWC (Fig. 1). The test procedure was as follows. At each engine Lambda (actual/stoichiometric air/fuel ratio), supplementary air was first used to study the oxidation effect of the Catalytic VPR. By adjusting the needle valve in the additional gas supply route, the mass flow rate of the additional air was controlled to give the Lambda meter reading that was 0.1, 0.2 or 0.3 above the Lambda that the engine was operating at. At each Lambda meter reading, the mass flow rate of the additional gas ($MFM_{add\ gas}$) was measured by MFM 3 and was recorded. Then, the air supply was swapped with nitrogen (N_2) to investigate the dilution effects of additional gas on the PM emissions. At each engine operating point, the needle valve was adjusted to let MFM 3 give the same readings as those recorded in the experiments with additional air. By comparing the two sets of results (additional air against N_2), the oxidation effect and dilution effect of the additional gas can be examined separately. The VPR Dilution Factor (VPR-DF) is defined as:

$$\text{VPR-DF} = 1 + (\text{MFM}_{\text{add gas}} / \text{MFM}_{\text{exhaust}}) \quad (3)$$

When testing with additional air at stoichiometric conditions, the VPR-DF is the same as the Lambda meter reading. The test point conditions are listed in Table 2.

In the TD test, the exhaust was sampled upstream of the TWC (Fig. 1). The TD was tested under different engine operating conditions (Table 2), including early single injection and double stratified injection, stoichiometric and rich combustion, with and without dilution. The engine coolant temperature was set to 20^oC.

3. Main Results

VPR tests1: Effect of Temperature and Residence Time

- Temperatures of Pre and Post VPR increase as the mass flow rates of the exhaust become higher (Fig. 2).
- VPR has more effect on the nucleation mode particles than accumulation mode particles (Fig. 3).
- Fig. 4 shows a representative raw size distribution from the DMS data and its lognormal fitting, which was taken Pre-VPR under 250^oC VPR temperature and 0.14 g/s mass flow of exhaust. It can be seen that the bi-lognormal result fits the trend of the raw data very well. As the lognormal fitting is very useful in eliminating the noise in the raw data at both the high and low end of the particle size range, the lognormal fitting results are used in the following analysis.

VPR tests2: Effects of Dilution Factor

- When excess air is added it can be seen that hydrocarbon oxidation is very effective, so that any hydrocarbons desorbed from the PM will be oxidised (Fig. 5).

• Fig. 6 shows the normalized specific total particle number and mass concentrations calculated from lognormal fitting to the data under various test conditions. Comparing the Post-VPR with the Pre-VPR particle emissions, there is a consistent reduction in the total number which is independent of the dilution factor, and this is more clearly seen with the rich mixture (lambda = 0.9). The normalized specific PM emission is defined as:

$$\frac{\text{Particle Concentration} \times \text{Dilution Factor}}{\text{Pre - VPR Particle Concentration}}$$

• Data after normal fitting are used in Fig. 7, where the data from Lambda = 0.9 with a Dilution Factor of 1.2 has been selected as a representative data set. The fitted lognormal data have been used, since this eliminates the effects of noise in the measurements. Since the European legislation prescribes the use of a VPR, this has been achieved numerically by using Equation 1. The nucleation mode particle number concentration is lower than the accumulation mode particle number concentration because the exhaust sample is after the TWC. The reduction in the nucleation mode particle number concentration is greater than for the accumulation mode particles. Also, as would be expected from Fig. 7 there is no difference between air and nitrogen as diluents.

• Further analyzing the total number ratio (Post-VPR/Pre-VPR) for the total PM, nucleation mode and accumulation mode (Fig. 8), it can be seen that at each measurement point for stoichiometric engine operation, the number ratios are in the following order: nucleation mode < Total PM < accumulation mode; this is not always seen for the rich operation cases. Although the oxidation effect of the Catalytic VPR has been verified by the HC results (Fig. 5), it seems that when engine was running rich of stoichiometric, the oxidation effects did not play much role in reducing the particle emissions. Apart from chemical reactions, some physical processes were taking place in the Catalytic VPR as well.

VPR tests2: Effects of Dilution Factor

• There is more reduction in the number of nucleation mode particles than of accumulation mode particles as the exhaust flows through the TD, with or without dilution air.

• the number ratios are in the following order:

nucleation mode < Total PM < accumulation mode;

• The transmission efficiencies increase as the particle size increases.

• Without dilution and for rich engine operation, the transmission efficiencies of large particles decreased compared to stoichiometric operation.

• With dilution air, because the P_n of small size particles is relatively low, there is greater signal noise in the transmission efficiency for small size particles.

4. Discussion

• On raw engine exhaust, nucleation mode particles contribute a large portion of the total particle number but only contribute a small portion of the total particle mass. The VPR exhibited marked elimination effects on particles, especially the smaller size (nucleation mode) particles.

• The VPR temperature and exhaust residence time ($MFM_{exhaust}$) did not show much effect on VPR performance. The VPR transmission efficiencies for different size particles all showed similar trends at various VPR temperatures and $MFM_{exhaust}$.

• When Post TWC exhaust was introduced to the VPR, with rich combustion, there was still no noticeable effect with increasing additional air on the VPR performance. However, the oxidation effect of the VPR on HC emissions was significant.

• For each air-fuel ratio, the transmission efficiency of the VPR did not change much with different types and varying amounts of additional gas. The reduction in the particle number through VPR is most likely to be due to physical processes.

- At the temperature of 450^{o}C, the thermo-denuder showed a more significant reduction effect on nucleation mode than accumulation mode particles.
- With a rich mixture and without dilution air, the penetration of large size particles was reduced compared to that of stoichiometric engine operation.
- With hot air dilution, the concentration of nucleation mode particles reduced to a very low level, leading to a drop in the signal to noise ratio at small size particles. At these points, the effects of the TD on the nucleation mode particles are less marked compared to without dilution.

References

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Testing of a Volatile Particle Remover (VPR) and a Thermo-denuder (TD) Using a GDI Engine

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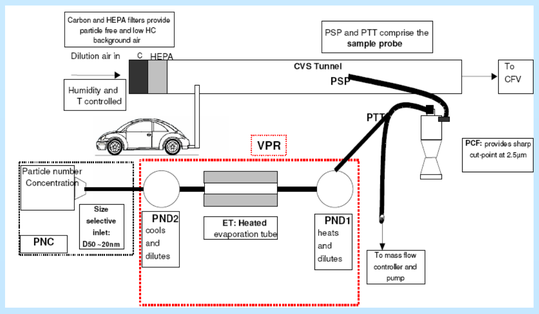
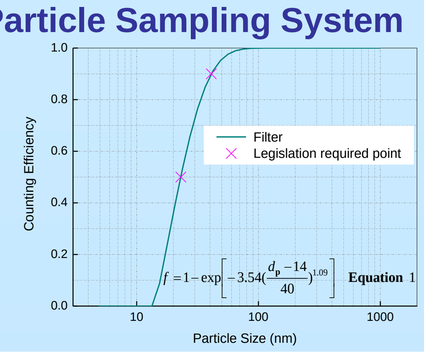
Introduction

A volatile particle remover (VPR) system is required by the European PMP programme. So, it is of interest to investigate whether an oxidation catalyst or a thermo-denuder can achieve the transmission efficiency required by the legislation, as well as to study their effects on PM emissions from a DISI engine.

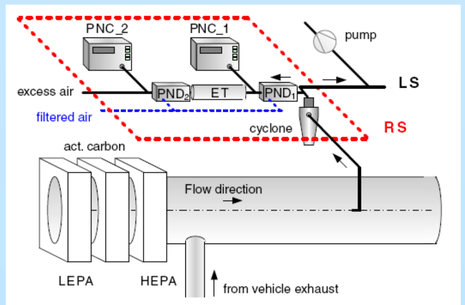
Legislation Requirement

Schematic of Recommended Particle Sampling System





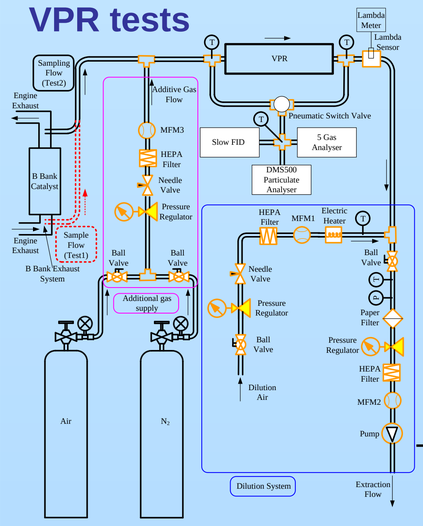
Reference system (RS).
PND1: primary diluter,
PND2: secondary diluter,
ET: evaporation tube,
LEPA: low efficiency particle filter,
HEPA: high efficiency particle filter,
PNC: particle number counter



PMP EU: J. Andersson, B. Giechaskiel, R. Muñoz-Bueno, E. Sandbach, and P. Dilara. Particle Measurement Programme (PMP) Light-duty Inter-laboratory Correlation Exercise (ILCE_LD) Final Report. 54th GRPE, 4-8 June 2007, agenda item 3. GRPE-54-08-Rev.1.

Experimental Set-up

VPR tests



TD tests

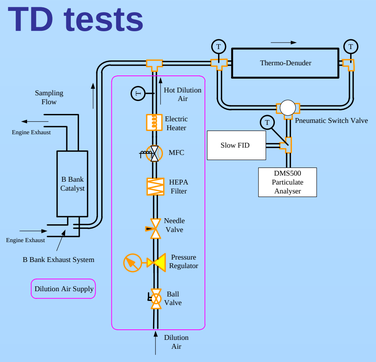


Fig. 1 Experimental Set-up

Table 1 VPR Tests Conditions (1500rpm, Single Injection)

Residence times (s) for VPR Test 1

VPR Temperature / °C	$MFM_{exhaust}$ / (g/s) 0.02	0.09	0.11	0.14	0.22
150	15.9	3.36	2.68	2.05	1.24
250	14.8	3.01	2.35	1.76	1.08
350	13.8	2.98	2.29	1.71	1.02

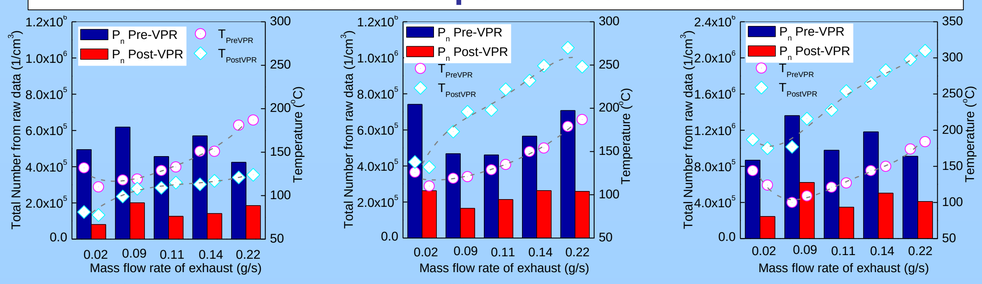
Mass Flow of Additional Gas (g/s) for VPR Test 2

Engine Lambda	Additional Gas	DF 1	1.1	1.2	1.3
1	Air	0	0.02	0.04	0.06
	N_2	0	0.02	0.04	0.06
0.9	Air	0	0.02	0.04	0.06
	N_2	0	0.02	0.04	0.06

Table 2 TD Tests Conditions

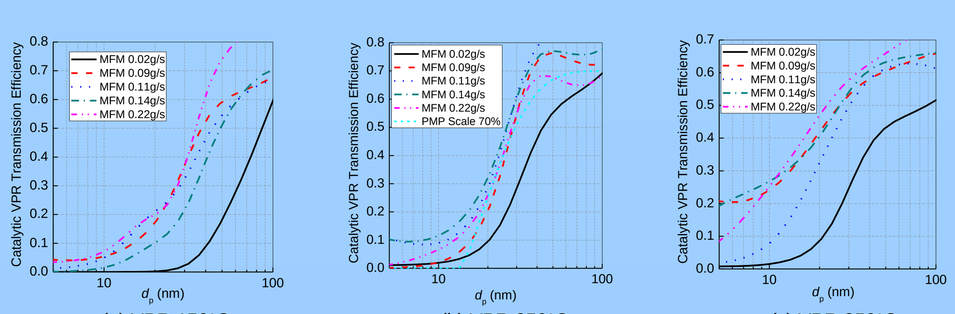
	SIN1 320 1.0	SIN1 320 0.8	SIN1 310 0.8	SP1 320 1.0
Engine:	V8			
Fuel:	ULG			
TD temperature (ºC):	450			
Speed (rpm):	800			
Torque (N.m):	80			
Fuel pressure (bar):	150 max			
Ignition timing:	-2º bTDC			
Injection mode:	Single	Single	Single	Split
1st injection timing:	320 ºCA bTDC	320 ºCA bTDC	310 ºCA bTDC	320 ºCA bTDC
2nd injection timing:	-2 ºCA bTDC	-2 ºCA bTDC	-2 ºCA bTDC	-2 ºCA bTDC
2nd injection width (ms):	0.25	0.25	0.25	0.25
Relative AFR:	1.0	0.8	0.8	1.0
IVO:	24ºCA aTDC			
IVC:	244ºCA aTDC			
EVO:	224ºCA bTDC			
EVC:	26ºCA aTDC			
Coolant (ºC):	20			

VPR tests1: Effect of Temperature and Residence Time



(a) VPR 150ºC (b) VPR 250ºC (c) VPR 350ºC

Fig. 2 Pre and Post VPR temperatures with different mass flow rate of exhaust ($MFM_{exhaust}$) and different VPR temperatures (refer to Table 1).



(a) VPR 150ºC (b) VPR 250ºC (c) VPR 350ºC

Fig. 3 Number transmission efficiencies versus d_p with different sample flow rates taken from the engine exhaust ($MFM_{exhaust}$) and different VPR temperatures (refer to Table 1).

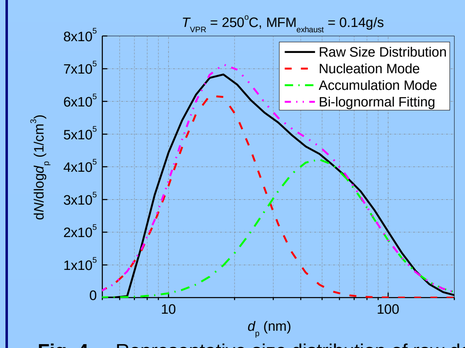


Fig. 4 Representative size distribution of raw data and its lognormal fitting (Pre VPR sampling, VPR 250ºC, $MFM_{exhaust}$ = 0.14g/s, refer to Table 1).

• Temperatures of Pre and Post VPR increase as the mass flow rates of the exhaust become higher (Fig. 2).
• VPR has more effect on the nucleation mode particles than accumulation mode particles (Fig. 3).
• Fig. 4 shows a representative raw size distribution from the DMS data and its lognormal fitting, which was taken Pre-VPR under 250ºC VPR temperature and 0.14 g/s mass flow of exhaust. It can be seen that the bi-lognormal result fits the trend of the raw data very well. As the lognormal fitting is very useful in eliminating the noise in the raw data at both the high and low end of the particle size range, the lognormal fitting results are used in the following analysis.

VPR tests2: Effects of Dilution Factor

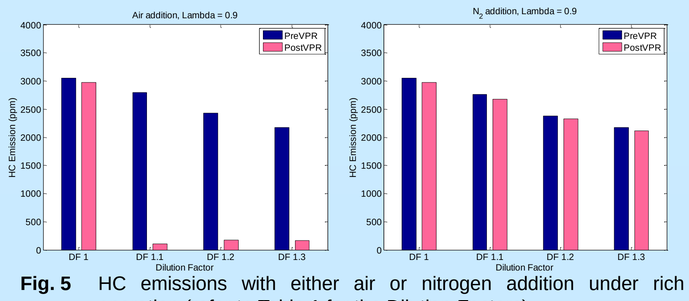


Fig. 5 HC emissions with either air or nitrogen addition under rich operation (refer to Table 1 for the Dilution Factors).

• When excess air is added it can be seen that hydrocarbon oxidation is very effective, so that any hydrocarbons desorbed from the PM will be oxidised (Fig. 5).

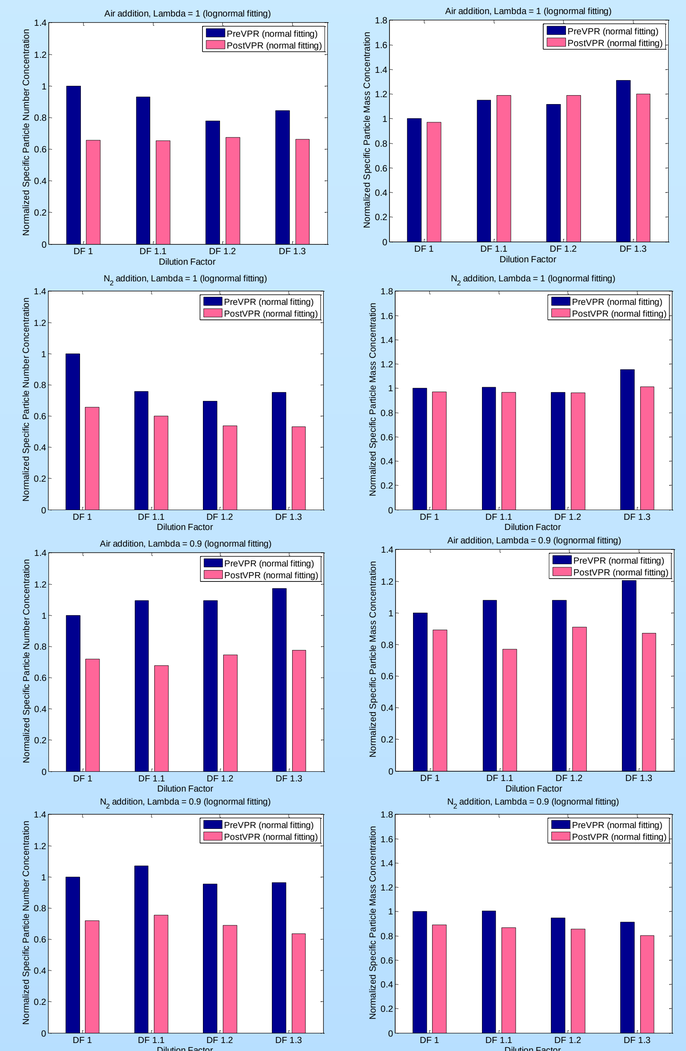


Fig. 6 Normalized specific particle number and mass concentrations with either air or nitrogen addition and Lambdas of 1.0 and 0.9 (refer to Table 1 for the Dilution Factors).

• Fig. 6 shows the normalized specific total particle number and mass concentrations calculated from lognormal fitting to the data under various test conditions. Comparing the Post-VPR with the Pre-VPR particle emissions, there is a consistent reduction in the total number which is independent of the dilution factor, and this is more clearly seen with the rich mixture (lambda = 0.9). The normalized specific PM emission is defined as:

$$\frac{\text{Particle Concentration} \times \text{Dilution Factor}}{\text{Pre - VPR Particle Concentration}}$$

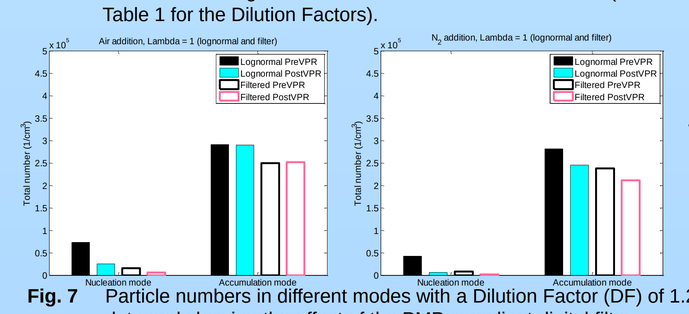


Fig. 7 Particle numbers in different modes with a Dilution Factor (DF) of 1.2 (refer to Table 1) obtained using lognormal fits to the Pre and Post VPR data and showing the effect of the PMP compliant digital filter.

• Data after normal fitting are used in Fig. 7, where the data from Lambda = 0.9 with a Dilution Factor of 1.2 has been selected as a representative data set. The fitted lognormal data have been used, since this eliminates the effects of noise in the measurements. Since the European legislation prescribes the use of a VPR, this has been achieved numerically by using Equation 1. The nucleation mode particle number concentration is lower than the accumulation mode particle number concentration because the exhaust sample is after the TWC. The reduction in the nucleation mode particle number concentration is greater than for the accumulation mode particles. Also, as would be expected from Fig. 7 there is no difference between air and nitrogen as diluents.

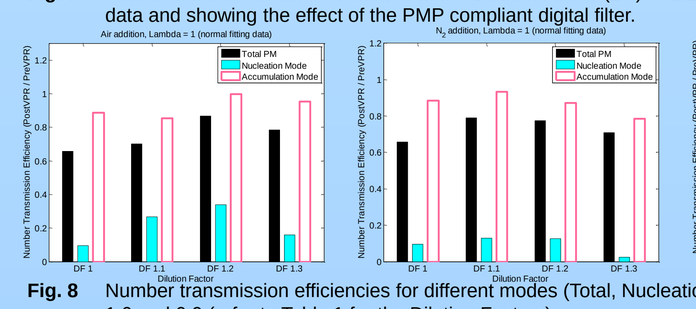


Fig. 8 Number transmission efficiencies for different modes (Total, Nucleation and Accumulation) with either air or nitrogen addition and Lambdas of 1.0 and 0.9 (refer to Table 1 for the Dilution Factors).

• Further analyzing the total number ratio (Post-VPR/Pre-VPR) for the total PM, nucleation mode and accumulation mode (Fig. 8), it can be seen that at each measurement point for stoichiometric engine operation, the number ratios are in the following order: nucleation mode < Total PM < accumulation mode; this is not always seen for the rich operation cases. Although the oxidation effect of the Catalytic VPR has been verified by the HC results (Fig. 5), it seems that when the engine was running rich of stoichiometric, the oxidation effects did not play much role in reducing the particle emissions. Apart from chemical reactions, some physical processes were taking place in the Catalytic VPR as well.

TD tests

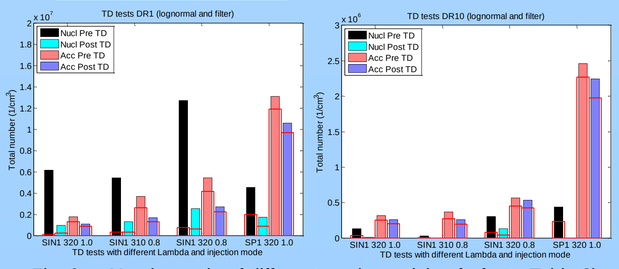


Fig. 9 Number ratio of different mode particles (refer to Table 2).

Fig. 10 Number ratio of different mode particles (refer to Table 2).

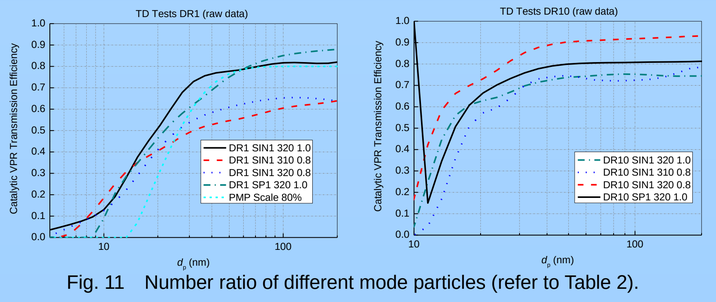


Fig. 11 Number ratio of different mode particles (refer to Table 2).

•There is more reduction in the number of nucleation mode particles than that of accumulation mode particles as the exhaust flows through the TD, with or without dilution air.

•the number ratios are in the following order:

nucleation mode < Total PM < accumulation mode;

•The transmission efficiencies increase as the particle size increases.

• Without dilution, and at engine rich operation, the transmission efficiencies of large particles decreased compared to stoichiometric operation.

• With dilution air, because the P_n of small size particles is relatively low, there is more signal noise in the transmission efficiency at small particle sizes.

Conclusions

• On the raw engine exhaust, nucleation mode particles contribute a large portion of the total particle number but only contribute a small portion of the total particle mass. The VPR exhibited marked elimination effects on particles, especially the smaller size (nucleation mode) particles.
• The VPR temperature and exhaust residence time ($MFM_{exhaust}$) did not show much effect on VPR performance. The VPR transmission efficiencies for different size particles have shown similar trends at various VPR temperatures and $MFM_{exhaust}$.
• When Post TWC exhaust was introduced to the VPR, with rich combustion, there was still not a noticeable effect with increasing additional air on the VPR performance. However, the oxidation effect of the VPR on HC emissions was significant.
• For each air-fuel ratio, the transmission efficiency of the VPR did not change much with different types and varying amounts of additional gas. The reduction of particle number through the VPR is more likely to be due to the physical processes.
• At the temperature of 450ºC, the thermo-denuder has shown a more significant reduction effect on nucleation mode than accumulation mode particles.
• With a rich mixture and without dilution air, the penetration of large size particles reduced compared to that with stoichiometric engine operation.
• With hot air dilution, the concentration of nucleation mode particles reduced to a very low level, leading to a fall in the signal to noise ratio for small size particles. At these points, the effects of the TD on nucleation mode particles are less marked compared to that of the conditions without dilution.

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