

Study on Performance Characteristics of Thermodenuder and Using It to Control Vapor Emission for Engine Exhaust

Garvjeetsingh

Department of Mechanical Engineering
K.J. Somaiya College of Engineering, Vidyavihar, Mumbai
garvjeet.s@somaiya.edu
Mob. 8600202070

Dr. S.S. Bhusnoor

Department of Mechanical Engineering
K.J. Somaiya College of Engineering, Vidyavihar, Mumbai
siddappabhusnoor@somaiya.edu
Mob. 9920534514

Abstract: This study consists of experimental studies carried out by various researchers on deposition of volatile particulate matter in a thermodenuder (TD) at various gas inlet temperatures. This study also covers Penetration efficiency of volatile particulate matter using different empirical equations at different flow and temperature of hot gas. With this literature understanding an experimental setup was developed to study the transport and control of vapor emission from IC Engine exhaust at various gas flow rates and for different particle sizes.

Keywords: Thermodenuder (TD), Penetration efficiency (η_p), Ultrafine particles (UFP), Thermophoresis, Mass fraction Remaining (MFR)

I. INTRODUCTION

The main source of air pollution in urban areas is particulate matters (PM) from vehicles, factories, incinerators etc. More specifically, combustion particles found in diesel emissions have been of great concern in the past few years, because of their adverse effects on health and their prominence in the vicinity of roads, especially in urban areas. These particles generally consist of a non-volatile core, mainly elemental carbon, on which volatile components condense when the exhaust gas cools. Therefore, separate measurements of the volatile and non-volatile components are needed to characterize the fraction of non-volatile carbon in the particles.

(Park et al 2008)

Separate measurement of volatile and non-volatile fractions of atmospheric aerosols have recently become an area of great importance, partly because non-volatile carbonaceous particles might cause respiratory illness. Materials which are volatile below the temperatures of 250°C are called as volatile whereas, non-volatile materials are those which are volatile only above temperatures 250°C. Carbonaceous materials represent the dominant fraction of non-volatile submicrometer particles in anthropogenically influenced regions. Therefore, volatility measurements are necessary for separation of non-volatile carbon fraction from particles.

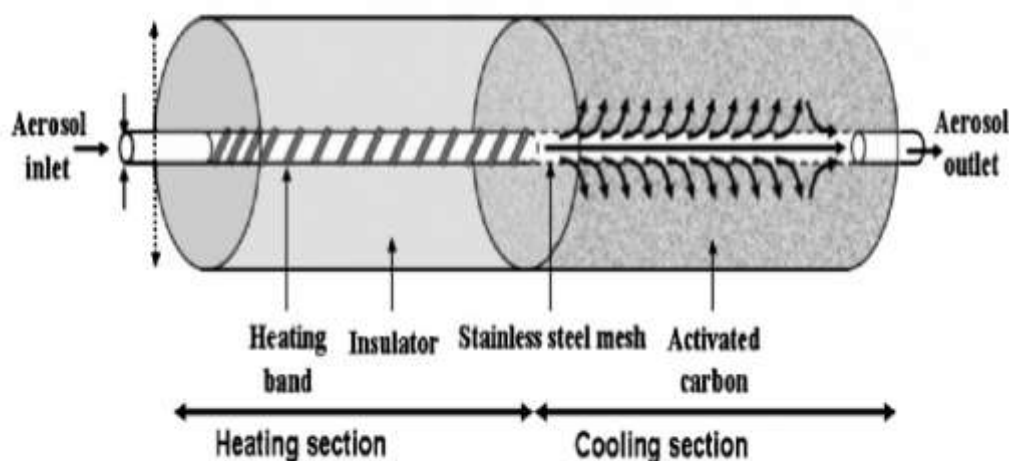


Figure 1 Schematic diagram of Thermodenuder device. (Park et al 2009)

Fig. 1. Shows a basic schematic of TD. A TD is generally made up of two sections, 1st is the heating section and the 2nd is the cooling section. The basic function of the heating

section is to heat up the aerosol to a predetermined/preselected temperature so as to evaporate all the volatile matter present in the aerosol. Further this heated

aerosol is made to go through cooling section which is already filled with activate carbon. This activated carbon absorbs the volatile fraction and stabilizes it. Therefore, the aerosol coming out comprises only of the non-volatile environment friendly particles.

The thermophoretic effect and the diffusional processes are the major cause of particle loss which further results in lesser transport efficiency for the TD. Also, the evaporation of the volatile species is strongly affected by the heating section temperature profile. Sometimes due to low residence time at a set point temperature, there are chances that some portion of volatile matter might remain on the particle instead of getting evaporated. On the other hand, it is also important to make sure that the cooling process is to be done particularly in the cooling unit, or else the probability of re-condensation of vapor on the particle surface increases. In order to avoid this re-condensation, activated carbon is generally used as an absorbent material.

Although, it is very difficult to mention the exact time required for the complete evaporation of volatile matter as the process is largely dependent on size of the particles and their composition. Therefore, a good TD device should have

both i.e longer residence time and size compatibility as well. (wehner et al 2002)

II. MATERIALS AND METHODS

A typical output of a thermodenuder experiment is the fraction of the initial organic aerosol mass that remains (referred to here after as the Mass Fraction Remaining, MFR) after the aerosol has been exposed to the thermodenuder temperature T_{TD}.

The MFR depends among other factors on;

- 1) How far from equilibrium temperature the particle and vapor phases are when they are first brought to the TD temperature;
- 2) How fast the mass transfer from the aerosols to the vapor phase is;
- 3) What are the particle and vapor losses in the TD.

In realistic TD applications the sampled aerosol is cooled back to ambient temperatures after heating, and in many current applications this is done with a special cooling section whose walls can be coated with absorptive material to remove the vapors to prevent re-condensation. The design of the cooling section is thus likely to affect the output of a realistic TD experiment. (Riipinen et al 2009)

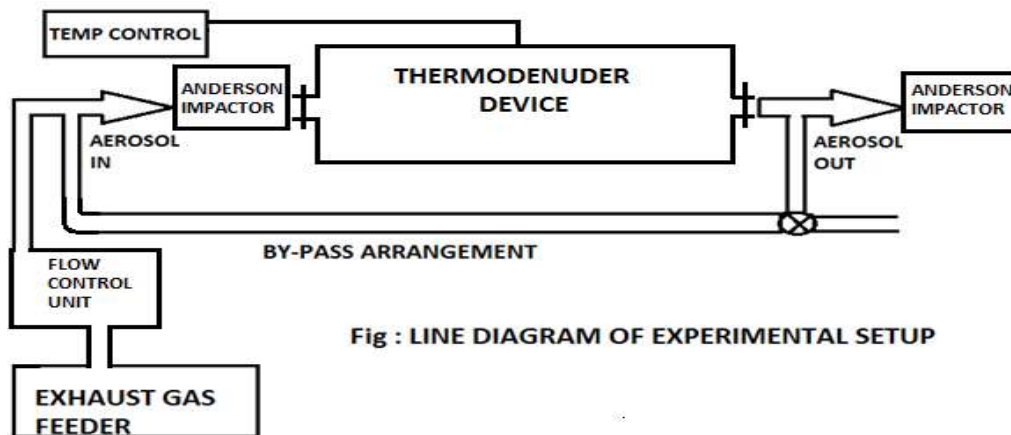


Fig : LINE DIAGRAM OF EXPERIMENTAL SETUP

Figure 2 Line Diagram of our experimental setup.

Fig. 2. Shows the line diagram of our laboratory experimental setup. Wherein we are interested in controlling of vapor emissions coming out of IC Engine exhaust. For this purpose, the exhaust gas will be made to go through a device known as thermodenuder, but only after controlling its discharge to required value using a flow control device called Rotameter. Two Anderson impactor will also be used

to measure particle concentration both at inlet and outlet of our TD. A temperature control unit will be incorporated to check the temperature profiles for both heating section and cooling section. The overall difference in the particle concentration at inlet and outlet will help us to find out the particle deposition inside the TD device.

Table 1 Equipment and components.

Sr. No.	Component	Type of Material	Dimensions (mm)	Quantity
1.	Inner Cylindrical Tube (heating side)	Stainless steel	Diameter – 20 Length – 600 Thickness – 0.5	1
2.	Inner Cylindrical Tube (cooling side)	Wire mesh Stainless steel	Diameter – 20 Length – 600	1

			Thickness –0.2	
3.	Circular Side plate	Ceramic	Thickness – 0.2	2
4.	Holding Rings	Stainless steel		2
5.	Insulation	Fine sand	-	-
6.	Heating coil	-	Length – 500	1
7.	Thermocouples	-	-	10
8.	Adsorption material	Activated Carbon	-	-
9.	Outer Cylindrical Tube	Stainless steel	Diameter – 200 Length – 500 Thickness – 1	2
10.	Rotameter	-	-	1
11.	Anderson Impactor	-	-	2

$$P_d = 1 - 5.5u^{2/3} + 3.77\mu \quad \text{for } u < 0.009$$

Where u is a dimensionless deposition parameter given by

$$u = DL/Q$$

Here, D (m²s⁻¹) is the diffusion coefficient of the particles, L(m) is the length of the tube and Q(m³s⁻¹) is the volumetric flow rate through the tube. In the case of a coiled tube, which enhances the formation of secondary flow, the particle penetration efficiency (Pd,coil) can be estimated as : (yook and Pui, 2006)

III. THEORETICAL MATHEMATICAL MODEL

In this section we resume the theoretical and semi-empirical equations that govern the particle losses inside a tube. The particles can be deposited along the system by diffusion, sedimentation, thermophoresis and electrostatic forces. Since the aim in this study is to focus on particles with mobility diameter (D_p) smaller than 200 nm, sedimentation losses are not considered. All the tubing in the system is electrically conductive in order to minimize electrostatic losses, which were considered negligible. Taking diffusion losses into account, the estimated particle penetration efficiency through a straight tube is given by (Hinds, 1999):

$$P_{d,coil} = 1 - 2.5104\zeta^{\frac{1}{3}} + 12.9919\zeta^{\frac{2}{3}} - 37.8238\zeta + 32.8761\zeta^{\frac{4}{3}} \quad \text{for } \zeta < 0.01$$

$$P_{d,coil} = 0.5526e^{-3.657\zeta} + 0.2250e^{-22.3\zeta} + 0.0726e^{-57\zeta} \quad \text{for } 0.01 < \zeta < 0.2$$

Here ζ is a non-dimensional parameter describing the particle deposition in coils assuming it is a by-product of secondary flow and Brownian diffusion. This parameter is expressed as follows:

$$\zeta = \frac{\delta Dt}{\alpha^2}$$

With δ represents the boundary layer thickness of the secondary flow normalized by the inner tube radius α (m), and t (s) the flow residence time inside the tube.

At ambient temperature, assuming an isothermal flow and aerosol particles in the UFP (Ultrafine Particle) size range, we can consider that particle deposition occurs mostly due to Brownian motion. Nonetheless, in a non-isothermal system with relatively cool walls, thermophoresis causes aerosol particles to move towards and deposit on the walls (Housiadas and Drossinos, 2005; Walsh et al., 2006).

Several studies have provided semi-empirical and numerical models to predict the thermophoretic deposition efficiency (η_{th}) inside a tube (Batchelor and Shen, 1985; Housiadas and Drossinos, 2005; Lin and Tsai, 2003; Romay, Takagaki, Pui, & Liu, 1999; Stratmann, Otto, & Fissan, 1994; Walker, Homsy, & Geyling, 1979). Lin and Tsai (2003) proposed the following semi-empirical equation for laminar flow:

$$\eta_{th} = 0.783(\text{Pr } k_{th}/\theta^*)^{0.94} \quad \text{for } 0.007 < \text{Pr} \cdot k_{th} < 0.19$$

And Housiadas and Drossinos (2005) an equation for laminar and turbulent flows based on 1D heat and mass transfer analysis:

$$\eta_{th} = 1 - (\theta^*/1 + \theta^*)^{\text{Pr } k_{th}}$$

In these models K_{Th} represents the thermophoretic coefficient and θ^* the temperature gradient between the wall and gas. In this study, the thermophoretic coefficient was determined according to Talbot, Cheng, Schefer, and Willis (1980). The gas Prandtl Number Pr used in is given by:

$$\text{Pr} = \mu C_p / K$$

Where C_p represents the specific heat (Jkg⁻¹K⁻¹), μ the dynamic viscosity (Nsec.m⁻²) and K the thermal conductivity (W m⁻¹K⁻¹). Temperature profiles inside the TDs affect also the diffusion of particles, which should be accounted for determining both the total particle losses required for predicting the penetration efficiency of heated TDs.

IV. RESULTS AND DISCUSSION

Table 2 comparison of parameters used by various researchers.

Researcher	Discharge Q (lpm)	Tube Dia. Di (m)	Velocity V (mtr.se c ⁻¹)	Reynolds no. Re	Penetration Efficiency $\eta\%$ at 25 °c		
					10n m	20n m	80n m

Wehner et al 2002	0.6	20	0.0318	12.12	-	88	-
Wu et al 2009	0.6	20	0.0318	12.12	-	98	-

Fierz et al 2007	0.315	8	0.1044	15.92	85	93	97
Mendes et al	0.3	8	0.0994	15.16	72	90	96
Park et al	0.6	22	0.026	10.90	-	93	98

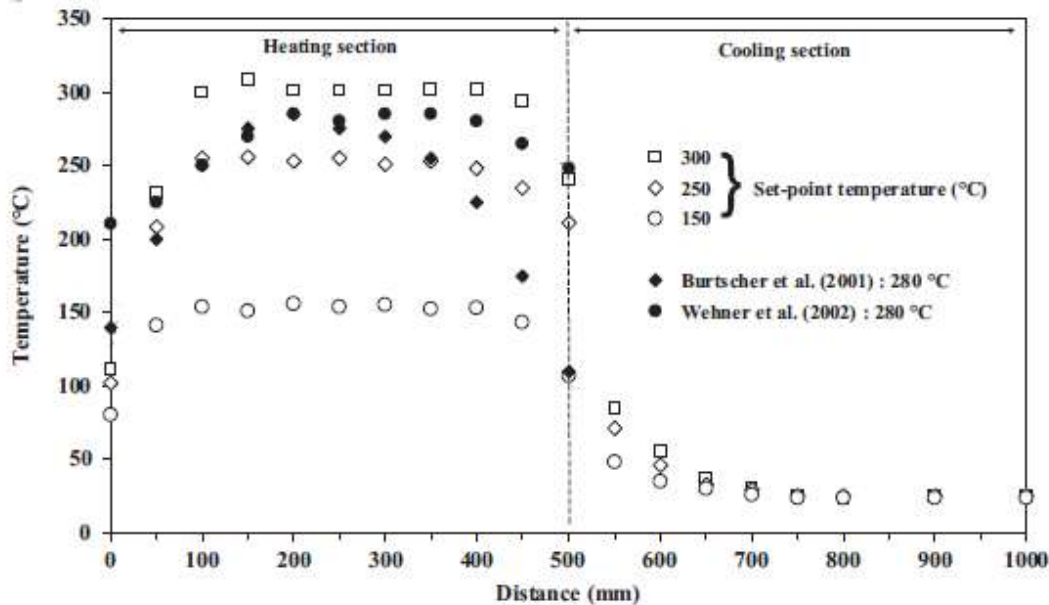


Figure 3 Temperature profile comparison of both heating section and cooling section for various set point temperatures. (Park et al 2009)

Fig. 3. Shows that compared to the result obtained by Burtcher et al. (2001), a more uniform temperature profile in heating section was obtained by Wehner et al. (2002). For all the experimental set point temperatures, the temperature increased relatively fast and reached the maximum temperature at a distance of approximately 200 mm from the entrance. The temperature remained uniform for a distance of 200-350 mm, but started to drop below the set point temperature after 400 mm.

increasing temperature, thermophoretic losses increased and the transmission efficiency decreased. At 25°C, the transmission efficiency of 20-nm particles was 88%, whereas at 280°C, the transmission efficiency decreased to 68%.

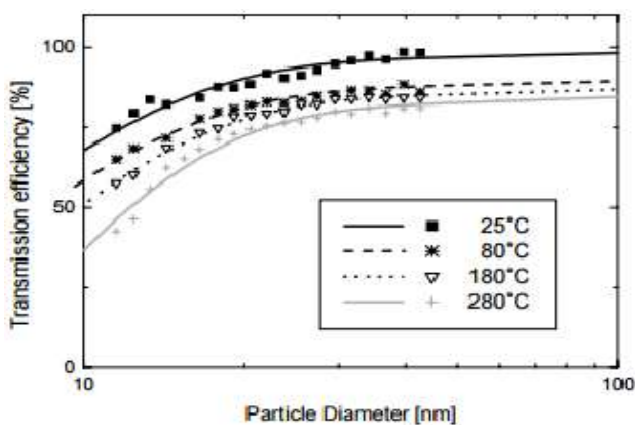


Figure 4 Particle size-dependent transmission efficiency of silver particles within the TD for different set-point temperatures. (Wehner et al 2002)

Fig. 4. Shows the measured transmission efficiency curves for the TD operated at a flow rate of 0.6 lpm for the heating section temperature from (25 to 280) °C. It was noted that with decreasing particle diameter, the losses increased due to the particle diffusion inside the TD. At 25°C, a transmission efficiency of 88% was measured for 20-nm particles, which decreased to 68% for 10-nm particles. With

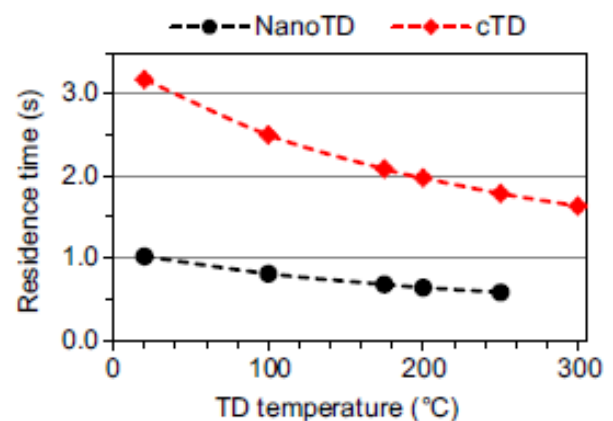


Figure 5 Aerosol residence time in the heated section of the Nano TD and the cTD, as a function of applied temperature and flow of 0.3 Lmin⁻¹. The markers represent the temperatures simulated in COMSOL Multi-physics software. (Mendes et al 2016)

Fig. 5. shows the estimated residence time in the heated section of each TD as a function of the applied temperature, at a flow rate of 0.3 Lmin⁻¹ (1 atm, 25 °C). The NanoTD has a residence time of 1.0 s at ambient temperature, which is reduced to 0.58 s (i.e., by 42%) at the maximum operating temperature of 250 °C, whereas the cTD exhibits a reduction in residence time from 3.2 s at ambient temperature to 1.79 s (i.e., by 44%) at 250 °C and 1.6 s (i.e., by 50%) at 300 °C.

V. CONCLUSION

The work done by different researchers on thermodenuder (TD) to measure Volatile fraction of aerosols using thermal desorption was studied. It was found out that more uniform temperature inside the heating section and a higher residence time are the key factors for improving the performance of a TD. Also the temperature at the exit of the heating section should be consistently higher in order to prevent particle re-condensation

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