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Design and Numerical simulation of Partial Flow Isokinetic Dilution Tunnel for Diesel Particulate Measurement

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***Abstract*:--Diesel engines are advantageous in terms of lower fuel consumption, lower unburned HC* and better fuel efficiency. Counter side they are disadvantageous in terms of high particulate emissions that results from fuel pyrolysis at high temperatures. These particulate emissions have antagonistic effect on both environment and human health. To regulate these diesel particulates, government is imposing stringent emissions norms on diesel engine exhaust. Therefore, it is important for all engine manufacturers to design and develop a system that is capable of measuring these particulate emissions. Further, diesel particulate matter is very complex structure, primarily composed of solid carbon with several absorbed species like ash, metallic abrasion particles, sulfates and silicates, which cannot be measured directly by analytical instruments based on direct detection method. The best approach to measure diesel particulate matter is based on the gravimetric method by using the device known as dilution tunnel. The present work focuses on design and numerical analysis of partial flow isokinetic dilution tunnel in order to determine the optimum mixing length to achieve complete mixing between the dilution air and exhaust sample. A commercial ANSYS FLUENT software has been used to perform the numerical simulations. To find optimum mixing length, various simulation test were conducted which can be categorized in three broad divisions. The first test consists of 9 different conditions based on variation in duct diameter and dilution ratio (DR) for constant duct length of 2500 mm. Results from first test shows that the shortest mixing length of 1250 mm was obtained for duct diameter of 150 mm when dilution ratio of 20:1 is maintained. Further, in order to reduce the mixing length, test 2 and 3 were conducted by introducing number of perforated plates and grid of cylinders only to best design of test 1. Results from test 2 and 3 shows that mixture gets uniform within 1000 mm of duct length when perforated orifice plate was used. The introduction of a grid of cylinder does not influence quick mixing of exhaust sample with diluted air.**

***Index Terms*— Dilution tunnel, dilution ratio, nucleation and agglomeration, particulate matter.**
*** HC: Hydrocarbon**

I. INTRODUCTION

Diesel particulate matter (PM) generally composes of three main fractions namely solid fraction (known as soot or SOL), soluble organic fraction (SOF) and sulfates, if the fuel contains sulfur [1]. PM having a diameter less than 100 nm [2] effects the human health most by directly penetrating the cell membrane, and entering into brain and blood of the human body. These harmful effects of PM have driven the nation to impose stringent BS-VI emission norms by 2019 for automotive industry. BS-VI requires up to 80% reduction in NOx (0.08 g/kmhr) and 66% reduction in PM (0.005 g/kmhr) compared to current BS-IV norms [3]. Apart from mass concentration, BS-VI norms also put strict limits on the number concentration of particulate matter emitted into the atmosphere [3]. That makes it necessary to study the number and mass concentration of diesel PM.

Dilution tunnel is the most common and cheapest device that is used to determine the diesel exhaust contribution to the total particulate content in the atmosphere in terms of particle mass and number distributions. It allows dilution of the raw exhaust with cold ambient air which initiates various microphysical processes such as nucleation, condensation and agglomeration of particles leading to alteration and formation of new diesel PM [4]. The main purpose of dilution tunnel sampling is to simulate processes in an atmosphere around the vehicle. Dilution tunnels are either full flow or partial flow [5]. A full flow dilution tunnel completely dilutes all the exhaust gases leaving the vehicle and then a small portion is sampled, while in partial flow dilution tunnel only a small fraction of the exhaust gas is diluted and then the whole diluted sample is passed through filter assembly carrying filter paper. There are three main types of partial flow dilution tunnel [6] namely; flow controlled systems with concentration measurement, flow controlled systems with flow measurement and

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isokinetic systems. Among all three types, an isokinetic system is the best suited system as the flow in the sampling probe is matched with the flow in the exhaust pipe in terms of velocity or pressure [7]. Further, it helps in achieving undisturbed and uniform flow at sampling probe [7]. L. M. Hildemann et al. [8] show that a dilution tunnel should closely simulate atmospheric dilution, provide enough residence time to allow condensation processes within the tunnel, minimize particle and vapour losses within the tunnel and finally avoid contamination of the dilution tunnel. Other researchers such as Chan et al. [9], Lyyranen et al. [10], Lipsky and Robinson [11], Yoon et al. [12] and Li et al. [13] presented various other dilution tunnel design that differs in terms of size, flow geometry and ease of portability. Chan et al. [9] presented strong evidence that for getting best results from the tunnel, particulate sampling should be done in a certain range of dilution ratio without exceeding a temperature of 52°C. Lipsky and Robinson [11] presented that particle mass distribution at the exit of dilution tunnel directly depends on tunnel geometry and Khalek et al. [14] shown that effective particulate trap depends on dilution ratio maintained inside the dilution tunnel. Nucleation mode is the first mode of particulate formation inside the dilution tunnel [14]. Further, nucleation mode directly depends on mixing of hot exhaust gas with cold ambient air which finally depends on flow condition. Overall, it may be concluded that the tunnel geometry, dilution ratio, and flow configuration inside the tunnel play an important role in measuring particulate matter distribution.

Computational fluid dynamics (CFD) helps to study the effects of various parameters like dilution tunnel length, the geometry of cross-section and dilution ratio on the performance of dilution tunnel, prior to fabrication [15]. This helps in deciding the optimum design and saves cost on fabricating different prototypes. Wang et al. [16] conducted CFD simulations of experimental data conducted by Lipsky et al. [11] on dilution tunnel. The CFD simulations match the experimental data; however, it was found that level of nucleation was different when the simulation was carried with dilution ratio (DR) 20 and DR 110 for the cross-flow tunnel. The above difference is validated in terms of differences in the relative humidity of the dilution air. The present work focuses on numerical simulation of partial flow isokinetic dilution tunnel with design modification such as the introduction of perforated tubes and a grid of cylinders within the tunnel so as to suggest an economical and efficient design for particulate mass measurement.

II.METHODOLOGY

Design Formulation

Dilution tunnels are full flow or partial flow [5]. A full flow dilution tunnel completely dilutes all the exhaust gases leaving the vehicle and then a small portion is sampled while in partial flow dilution tunnel only a small fraction of the exhaust gas is diluted and then the whole diluted sample is passed through filters. Partial flow dilution tunnel are of three types [6] namely, flow controlled systems with concentration measurement, flow controlled systems with flow measurement and isokinetic systems. Isokinetic systems are advantageous in terms of achieving undisturbed and uniform flow at sampling probe as flow in sampling probe is matched with the flow in the exhaust pipe in terms of velocity or pressure. The present study focuses on design and numerical analysis of various designs of partial flow isokinetic dilution tunnel in order to determine the effectiveness of rapid mixing design in achieving complete mixing between the dilution air and exhaust sample. Considering the basic requirements and restrictions imposed by ASTM standard E2515-11 [16], a 3D model (Fig. 1) of a partial flow isokinetic dilution tunnel is developed using SOLIDWORKS. The model is made up of four units namely air filter and intake blower unit, conditioning and preheating unit, mixing and agglomeration unit and finally filter assembly and exhaust unit. However, the numerical simulations are limited only to mixing and agglomeration unit, as mainly the dilution dynamics is affected by the design of this unit.

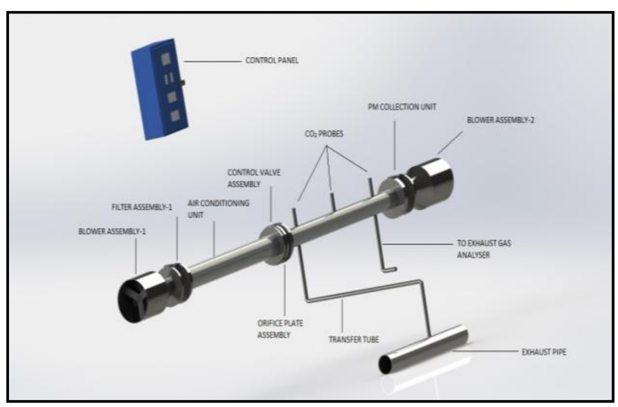

Fig. 1 Design of dilution tunnel prepared using SOLIDWORKS

Experimental Matrix

A commercial ANSYS FLUENT software has been used to perform the numerical simulations. CO_2 molar

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concentration is the main parameter that helps to get optimum mixing length by ensuring rapid and complete mixing of dilution air and exhaust gas sample.To find optimum mixing length, various simulation test were conducted which can be categorized in three broad divisions.

***Test 1*:** Total 9 simulations (Table 1) are conducted at constant duct length of 2500 mm with variation in duct diameter and dilution ratio (DR).

Table1. Experimental test matrix for TEST 1

Test No.	DR	10:1	15:1	20:1
1a	**100 mm**	√√	√√	√√
1b	**125 mm**	√√	√√	√√
1c	**150 mm**	√√	√√	√√

Test 2:

Optimum design from TEST 1 will be further analysed by introducing perforated orifice plate of internal diameter 47mm.

Test 3:

Optimum design from TEST 1 will be further analysed by introducing grid of cylinders of diameter 12 mm. Finally, the best design i.e. the design that requires minimum mixing length to achieve complete mixing between the dilution air and exhaust sample will be finally selected from above 3 tests.

Geometry Construction and Meshing

The CAD model of mixing and agglomeration unit is imported to Design Modeller part of ANSYS 15. The meshing is done using tetrahedral mesh. Fig. 2 shows the mesh geometry of mixing and agglomeration for one of the above test (Test 1a).

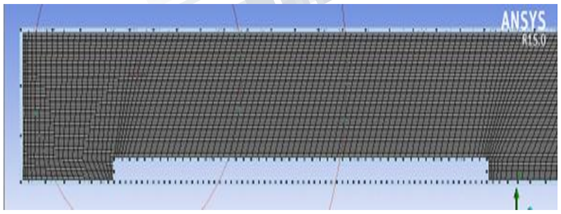

Fig. 2 Meshing for 100 mm diameter duct

A grid independence test is conducted to decide the optimum number of grids. Grids are refined by changing the horizontal length. Refinements of grids with horizontal length less than 3 mm and 1 mm, shows no changes in CO_2 concentration obtained at the outlet unit. Hence, it is chosen as the optimum grid size for conducting simulations. Standard k- ϵ model is used to solve the governing equations of the model.

Boundary Conditions

Boundary Conditions that are applied are as follows:

1. Air Inlet: Velocity: variable, temperature: 300 K, CO_2 molar fraction: 0 and O_2 molar fraction: 0.23.
2. Exhaust Inlet: Velocity: 12 m/s, temperature: 573 K, CO_2 molar fraction: 1and O_2 molar fraction: 0.

3. Walls: All the inner and outer surfaces of the tunnel are stationary walls.

**Above exhaust inlet conditions are selected for a mid-sized diesel engine running at 2500 rpm speed and full load condition.*

III. RESULTS AND DISCUSSION

The flow characteristics in the partial flow isokinetic dilution tunnel greatly dependent on relative velocities of sample exhaust and dilution air. For validating various dilution tunnel design, velocities are directly dependent on dilution ratio and diameter of the duct. Dilution ratio (DR) can be defined as:

$$DR = \frac{CO_2 \text{ concentration in exhaust}}{CO_2 \text{ concentration in diluted exhaust} - CO_2 \text{ Concentration in diluted air}}$$

Hence, the variation of CO_2 concentration is considered to be main output parameter for getting best and quick mixing of exhaust sample with dilution air inside the tunnel. Figure 3 shows various locations which are termed as series in graphs, along the circumference of tunnel duct where CO_2 concentration was measured. Total 9 locations or series were marked, each at a uniform distance of 0.01m from each other.

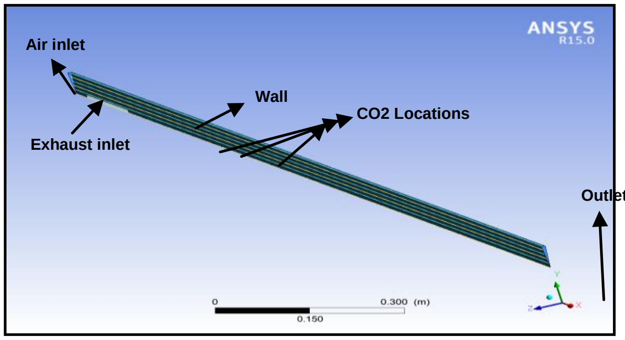

Fig. 3 Locations at which CO_2 concentrations are measured

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Results of TEST 1

Total 9 experiments were conducted during TEST 1 for getting the best optimum design in lieu of getting minimum length required for complete mixing of exhaust sample with dilution air. Test 1a is conducted at constant duct length of 2500 mm and duct diameter of 100 mm with variation in dilution ratio according to an experimental matrix. Results show that the best optimum design was obtained for duct diameter of 150 mm and duct length of 2500mm when dilution ratio of 20:1 was maintained. The velocity of air at air inlet was found to be 2.4 m/s and complete mixing occurs within 1.25 m length of duct length as shown in figure 4.

Further, in order to enhance quick mixing of exhaust sample with diluted air, perforated plates (TEST 2) and a grid of cylinders (TEST 3) were added to the best design of TEST 1. Figure 5 and 6 shows meshing for 150 mm duct diameter with the perforated orifice plate and a grid of cylinder. Results of TEST 2 and 3 shows that mixture gets uniform within 1m of duct length (fig. 7) when perforated orifice plate was used. The introduction of a grid of cylinder does not influence quick mixing of exhaust sample with diluted air.

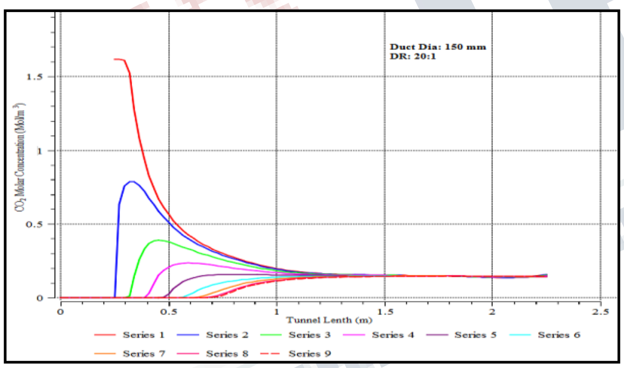

Fig. 4 Variation in CO_2 concentration for duct dia. 150 mm and DR 20:1

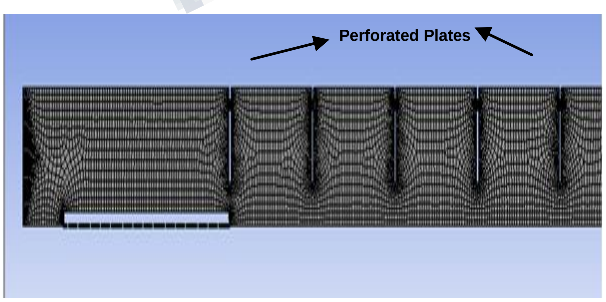

Fig. 5 Meshing for 150 mm duct diameter with perforated Orifice plate

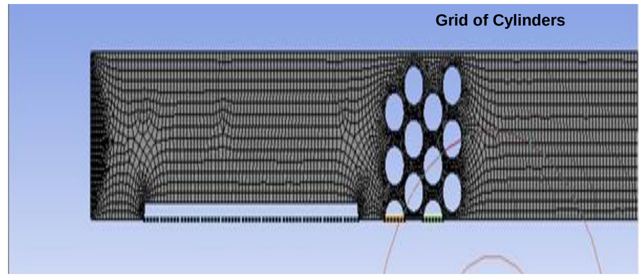

Fig. 6 Meshing for 150 mm duct diameter with grid of cylinders

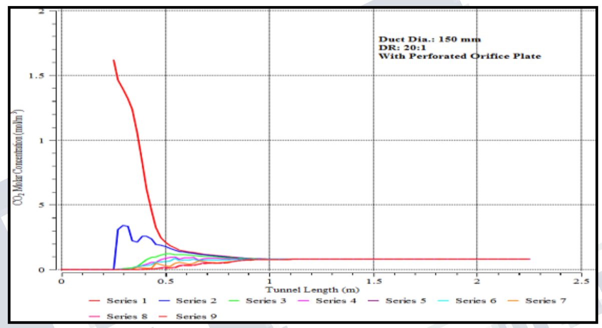

Fig. 7 Variation in CO_2 concentration for duct dia. 150 mm and DR 20:1 with perforated orifice plates

IV. CONCLUSION

Various simulations test were performed to investigate the effects of various designs of partial flow isokinetic dilution tunnel in view to suggest the best optimum design. The best otimum design was based on getting minimum length required for complete mixing of exhaust sample with dilution air. Through various simulation tests it is found that the length required to achieve uniform mixing of exhaust gases and dilution air decreases with increase in duct diameter. Further, as the flow rate is increased, the length required to achieve uniform mixing within the duct gets increases. Finally, the use of perforated orifice plate greatly enhances the mixing characteristics of the dilution tunnel. Finally, a new and improved design of partial flow isokinetic dilution tunnel can be created using a perforated plate for 2500 mm length and 150 mm diameter keeping dilution ratio constant at 20:1.

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