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The Design of a Full Flow Dilution Tunnel with a Critical Flow Venturi for the Measurement of Diesel Engine Particulate Emission

An appropriate type of dilution tunnel is chosen, based on the international standards, user's needs and the manufacturer's requirements. During the design process, a number of restrictions specified in the standards for emission and Venturis were taken into account. The data required to address basic concepts were obtained from numerous emission tests performed at the IMR Institute. A short algorithm of calculation of the critical flow Venturi (CFV) is also presented. Specific attention is paid to the problems of the measurement of particulate emissions using the dilution method, which does not allow us to use the unique thermodynamic and flow parameters. A method of evaluation of particulate emissions for two extreme cases which were expected during the tests was adopted. Using the results of calculations, a full flow dilution tunnel with CFV was manufactured and tested at the IMR Institute.

Keywords: *diesel engine, exhaust emission, particulate matter, measurement, dilution tunnel, critical flow Venturi.*

1. INTRODUCTION

Remembering the importance of the problem of air pollution caused by particulate matter in theexhaust emissions of diesel engines, it is essential for any diesel engine manufacturer and its development unit to have a system for measuring these particulate emissions. For a small research laboratory, like the one at the IMR Institute, there is a clear need to have a simple, reliable and cheap system for testing engines of various sizes. Therefore, a decision was made to design our own system for engine exhaust particle emission testing within the IMR Institute.

The particulate emission measurements are rather different from the measurement of the gaseous components. In the measurements of the gaseous emissions, some specific properties of the gases measured are used, which enables the manufacturing of analytical equipment with adequate precision and repeatability [1,2]. Diesel engine exhaust particles do not have the unique physical or chemical properties which could be used in the detection method. The only appraoch used until now has been based on the gravimetric method. In this method the total mass of particles collected at the filter is estimated in the precisely measured and conditioned sample of exhaust gas, diluted with clean, dry air based on the precisely evaluated dilution ratio. This is a simple, but very demanding approach due to the numerous restrictions [3] which need to be met to enable good repeatibility and precision of testing.

The goal of the paper is to present a method of measurement of particulate emissions, and its implementation in a full flow dilution tunnel. The results of our selection of the critical flow Venturi, which is expected to measure and ensure constant diluted exhaust gas flow during the sampling procedure for diesel engine particulate matter, will be presented. The measurement method is shown to be compatible with European standards.

2. REQUIREMENTS AND RESTRICTIONS

Any particulate measurement system has to fulfil numerous demands and restrictions. Some of them are infered from the required standards, and some of them result from the experience gained through the emission measurement. The most crucial requirements are the following [2, 3, 8]:

1. The dilution of an exhaust sample by ambient air should not lead to any condensation in the measured sample and the conditions should be similar to ambient conditions after the exit of gases from an exhaust pipe. This means that the sample temperature has to be not greater than 325 K (52°C). The dilution ratio (i.e. the ratio between the dilution air and the exhaust) has to be greater than 4. At the same time, the temperature of the diluted gas must be greater than 293 K (20°C), in order to avoid the thermoforesis effect.
2. The tunnel should be sufficiently long to ensure complete mixing of the dilution air and exhaust gas prior to the sampling zone. The Reynolds number has to be more than 4000.
3. The de-humidifying of the dilution air is permitted, but the use of chemical de-humidifiers is forbidden.

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4. The sample filters must have a 0.3 μm particle size collection efficiency of at least 95% at a gas velocity between 0.4 and 0.8 m/s at the front of the filter.
5. The velocity of sample gas through the filter should remain between 0.35 and 0.80 m/s. The difference in pressure drops caused by the sample filters before and after the test should be lower than 25 kPa. This is an indicator of the maximum permitted filter loading. The minimum loading must be at least 465 μg/mm^2 of the stain area.
6. All parts of the dilution and sample systems which come into contact with raw or diluted exhaust emissions should be manufactured using electrically conductive and corrosive-resistant material. The natural choice is the stainless steel.
7. The depression at the engine inlet and the pressure in the engine exhaust pipe should be kept at maximum values specified by the engine manufacturer.

3. THE DESIGN CONCEPT

Two design concepts that meet the required standards are the full-flow and partial flow dilution systems [2, 3]. The main difference between them is the amount of exhaust gases being diluted. In the full-flow systems the exhaust gases are completely diluted and then a small portion is sampled, while in the partial flow systems only a small portion of exhaust gases is diluted and then the whole diluted sample is passed through the filters. Each concept has its advantages and disadvantages, which are summarised in Table 1.

Tunnel dimensions are estimated based on the maximum required flow rate of the exhaust gas and air for the dilution used for a given engine size. Regardless of the amount of exhaust gas flow at various engine speeds, the total flow through the tunnel (dilution air plus exhaust gas) should remain constant, but the ratio of dilution air and exhaust gas (i.e. the degree of dilution, DR - Dilution Ratio) is allowed to change. To perform measurements for such constant flow, two flow measurement systems can be used: the PDP (Positive Displacement Pump) system or the CFV (Critical Flow Venturi) system. The PDP system is accurate and simple, but it is very expensive and it has to be bought from abroad. The CFV system is more complex but it can be manufactured locally.

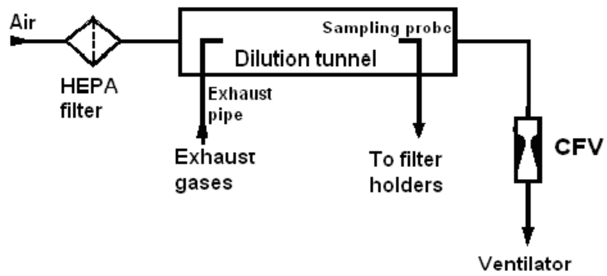

Figure 1. Schematic of a full-flow dilution tunnel

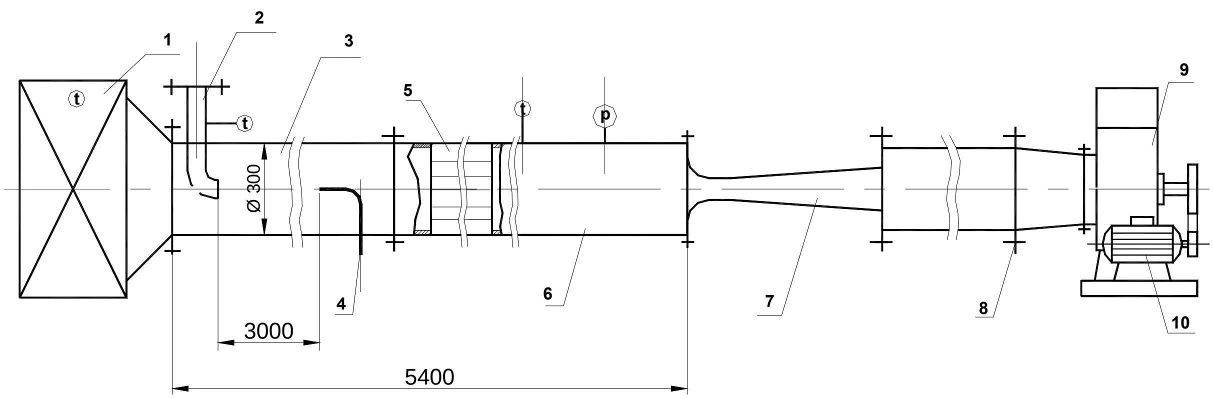

Figure 2. Drawing of a full-flow dilution tunnel [8]

1 - HEPA filter case; 2 - exhaust pipe; 3 – mixing section;4 – isokinetic sampling probe; 5 – slats for flow stagnation; 6 – flow stagnation section; 7 – CFV - critical flow Venturi; 8 - heater (optional); 9 – ventilator; 10 - ventilator drive.

Table 1. The advantages and disadvantages of the dilution concepts

	Full-flow dilution	Partial flow dilution
Advantages:	• Easy to design • Easy to handle and maintain • Reliable in operation • Possible upgrade in modules • Adopted as a reference system	• Small size • Easy to manufacture • Applicable for big swept volume engines • Low air consumption • Low power consumption
Disadvantages:	• Large dimensions • Not applicable for big swept volume engines • Need robust accessories • High power consumption	• Difficult to control of the process • Expensive and unreliable measuring system • Results differ depending on the method being used • Can not be used a the reference system

Remembering the above factors, a decision was made at the IMR Institute to design and manufacture a full-flow dilution tunnel with a CFV system. A schematic of such a system shown in Figure 1.

4. THE TUNNEL DESIGN

A technical drawing of a complete system is shown in Figure 2. During the system design, the previously mentioned requirements were taken into account. At the beginning of the design process, the following assumptions were made [8]:

1. The exhaust gas is a mixture of perfect gases with chemical structures and temperatures inferred from the earlier emission tests;
2. The dilution air is clean and dry at the temperature of 298 K (25°C) ±5K ,
3. The diluted gas is a homogenuous mixture of exhaust gas and dilution air;
4. The physical properties of diluted gas depend on the type and the operating regime of the engine being tested, i.e. on the concentration, chemical structure and temperature of the exhaust gases;
5. Solid pollutants in the diluted gas do not affect its density and molar mass;
6. The gas flow through the tunnel is considered to be one-dimensional and isentropic.

Special care was exercised during emission measurements based on the dilution of exhaust gases taking into account variations in the temperature and particulate concentration, since it is expected that the tunnel will be used for emission measurements for various engine sizes and operating regimes. Therefore, a method focused on the two extreme cases, which are expected during the tests, was used. In this method data inferred from former emission measurements performed at the IMR Institute were used.

These two extreme cases are as follows:

1. The engine with the largest swept volume operating at the regime of rated power (low dilution ratio, high temperature, high concentration of gaseous pollutants);
2. The engine with the smallest swept volume operating at idle (high dilution ratio, low temperature, low concentration of gaseous pollutants).

The physical properties of the diluted gas for both extreme cases are shown in Table 2. All other cases fall between these two extremes. The calculation of the tunnel components was performed for both cases and the size of the dilution tunnel was defined.

Figure 3. Front view of the dilution tunnel with the flange for the exhaust pipe

Figures 3 and 4 show the full flow dilution tunnel (front and rear views) and Figure 5 shows a set of filter holders. The main characteristics of the newly designed and manufactured dilution tunnel are the following [8]:

- Nominal flow rate 3000 m^3/h
- Tunnel diameter 300 mm
- Length of the mixing section 3000 mm
- Length of the flow stagnation section 1800 mm
- Reynolds number in mixing section > 179700
- Ventilator power 17.5 kW
- Flow control by CFV
- Diameter of the sampling filter holder 70 mm
- Tunnel material: high quality steel C.4580.

Figure 4. Rear view of the dilution tunnel with isokinetic sampling probe

Table 2. Physical properties of diluted gases in the tunnel for two types of operating regimes in engines [8]

Property	Symbol	The largest engine, rated power	The smallest engine, idle
Molar mass	M_{mix} (kg/mol)	$28.968*10^{-3}$	$28.99*10^{-3}$
Density	ρ_{mix} (kg/m^3)	1.030	1,148
Mixture temperature	T_{mix}	336.4 K (63,4 °C)	304.7 K (31,7 °C)
Isentropic exponent	κ	1.391	1.392
Compressibility factor	Z	1.0056	0.9968

Figure 5. Filter holders for particle collection

5. CRITICAL FLOW VENTURI DESIGN

When diluted exhaust gas accelerates through a restricted region, its density decreases and its velocity increases. In the region of the Venturi nozzle throat with minimal cross-sectional area, the maximal velocity is sonic, and further decreasing the downstream pressure will not increase the mass flow rate. This is referred to as a choked or critical flow.

Figure 6 shows a typical pressure-velocity relationship for a convergent-divergent nozzle through which a compressible fluid passes. As the downstream pressure p_{f3} decreases, the throat velocity c_t increases until the critical pressure ratio is reached at which the throat velocity is sonic. The critical pressure ratio is the ratio of the static pressure at the nozzle throat to the stagnation pressure for which the gas mass flow rate through the nozzle is maximal and the velocity is sonic.

Further decreases in the downstream pressure will not increase the mass flow rate. The flow is referred to as subsonic above the critical pressure ratio, and is critical to this ratio. In critical flow the throat velocity is always sonic, but the velocity increases in the diffuser section downstream from the nozzle, where a normal shock front occurs. Depending on the downstream pressure, four flow conditions can be expected:

1. For downsteam pressures greater than critical, the flow remains subsonic and may be calculated based on incompressible flow theory.
2. When p_{f3} is reduced to the value at which sonic throat velocity first occurred, the flow decelerates in the divergent section to a subsonic velocity; the gas expands isentropically to throat pressure and than returns to the higher downstream pressure.
3. Reducing the downstream pressure further will not alter the critical pressure ratio between the upstream and throat pressures, but the velocity in the divergent section is increased until a normal shock wave is formed. The flow across the shock is not isentropic, and the velocity abruptly changes from supersonic to subsonic.

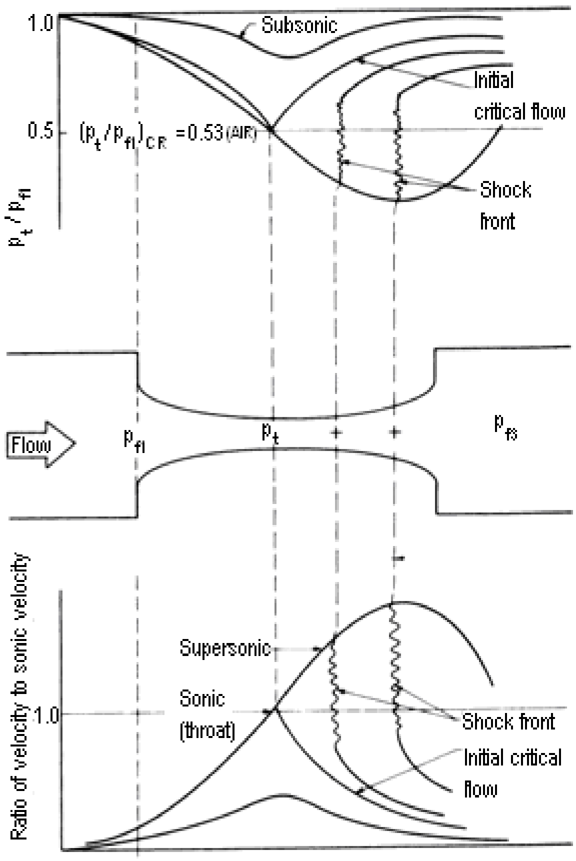

Figure 6. Pressures and fluid velocities for a Venturi nozzle [7]

4. The shock front location moves progressively downstream with further pressure reductions, until it no longer occurs within the divergent section. The flow then accelerates steadily throughout the nozzle and remains subsonic in the convergent passage, sonic at the throat, and supersonic within the divergent section.

The minimum downstream pressure at which critical flow is expected to be observed depends on the geometry and the isentropic exponent of the gas. Within the divergent section the choking pressure is approximately 5 to 10 % of the upstream pressure, but in the case without the divergent section it is approximately 50 % of the upstream pressure.

5.1. Calculation of the critical flow through the CFV

Data for computation of the CFV are typically available only for homogeneous dry gases and mixtures with constant chemical composition and without solid pollutants [4, 7]. These assumptions cannot be usedin our study due to significant variations in the measured gas physical properties during each test. Thus, the computations of CFV parameters were performed using actual input parameters (see Table 2) instead of those taken from the literature.

The calculations were performed for both limiting cases using the following algorhithm (given in ISO9300:2005) [4].

The critical flow rate for one-dimensional isentropic flow of a perfect gas is estimated as:

$$q_{mi} = \frac{A_* \cdot C_{*i} \cdot p_o}{\sqrt{(R/M) \cdot T_o}} \quad (1)$$

or

$$q_{mi} = A_* \cdot C_{*i} \cdot (p_o \cdot \rho_o)^{1/2} \quad (2)$$

where:

- A_* is the cross-sectional area of the Venturi nozzle exit
- p_0 is the absolute stagnation pressure of gas at the Venturi nozzle inlet
- R is the universal gas constant
- M is molar mass
- ρ_0 is gas density at stagnation conditions at the Venturi inlet
- T_0 is absolute stagnation temperature of the gas at the Venture inlet
- C_{*i} is the critical flow function for one-dimensional isentropic flow of a perfect gas)

$$C_{*i} = \gamma^{1/2} \cdot \left(\frac{2}{\gamma+1}\right)^{\left(\frac{\gamma+1}{2\cdot(\gamma-1)}\right)} \quad (3)$$

- γ is the ratio of the specific heat capacities at constant pressure (c_p) and constant volume (c_v) for a perfect gas.

Absolute stagnation pressure p_0 and temperature T_0 are linked by the following relations

$$\frac{p_o}{p_1} = \left(1 + \frac{\kappa - 1}{2} \cdot Ma_1^2\right)^{\frac{\kappa}{\kappa-1}} \quad (4)$$

$$\frac{T_o}{T_1} = 1 + \frac{\kappa - 1}{\kappa} \cdot Ma_1^2 \quad (5)$$

- p_1 is the absolute static pressure of gas at the nozzle inlet
- T_1 is the absolute temperature of gas at the nozzle inlet
- Ma_1 is the Mach number at the nozzle inlet static conditions (ratio of the axial gas velocity to the velocity of sound at the inlet of the Venturi nozzle)

$$Ma_1 = \frac{c}{c_v} \quad (6)$$

- c is the axial gas velocity at the inlet of the Venturi nozzle
- c_v is the velocity of sound at the Venturi nozzle inlet.
- κ is the isentropic exponent defined for the nozzle inlet. It is the ratio of the relative variation in pressure to the corresponding relative variation in density under elementary reversible adiabatic (isentropic) transformation conditions. Note that κ is not equal to γ except when c is equal to the velocity of sound.

$$\kappa = \frac{\rho \cdot c^2}{p}$$

For the flow in realistic conditions, the actual mass flow rate is computed from the following equation:

$$q_m = \frac{A_* \cdot C_d \cdot C_* \cdot p_o}{\sqrt{(R/M) \cdot T_o}} \quad (7)$$

or

$$q_m = A_* \cdot C_d \cdot C_R \cdot (p_o \cdot \rho_o)^{1/2} \quad (8)$$

where:

- C_d is the discharge coefficient for the Venturi nozzle

$$C_d = a - b \cdot \mathrm{Re}_d^{-n} \quad (9)$$

- parameters a, b and n are a=0.998, b=0.139, n=+0.2 [4], for a cylindrical nozzle throat and expected Re_d in the range of $3{,}5*10^5 < Re_d < 1{,}1*10^7$.
- Re_d is the Reynolds number in the Venturi nozzle

$$\mathrm{Re}_d = \frac{4 \cdot q_m}{\pi \cdot d \cdot \mu_0} \quad (10)$$

- d is the diameter of the Venturi nozzle
- μ_o is the dynamic viscosity of gas under stagnation conditions at the nozzle inlet
- C_* is the critical flow function which characterises the thermodynamic properties of a real gas isentropic one-dimensional flow between the inlet and the throat of a Venturi nozzle. Note that C_* is not equal to C_{*i}. Data for the values of the real gas critical flow function can be found in [4].
- C_R is the real gas critical flow coefficient. It is an alternative to the critical flow function, more convenient for gas mixtures. It is related to the critical flow function by the relation

$$C_R = C_* \cdot Z_o^{1/2} \quad (11)$$

- Z_o is the value of the compressibility factor under stagnation conditions at the nozzle inlet:

$$Z_o = \frac{p_o \cdot M}{\rho_o \cdot R \cdot T_o} \quad (12)$$

Using the dilution tunnel parameters, the nozzle cross-sectional area is calculated by iterations leading to the diameter of Venturi nozzle equal to 69.3 mm. These are the results of measurements of some parameters of the critical flow in the manufactured Venturi with a cylindrical nozzle [9, 10]:

- depression in nozzle throat: Δp=45195 Pa,
- mass flow rate: m=0.982 kg/s,
- flow speed in the nozzle throat: c_v=321.1 m/s
- volumetric flow rate: v=0.888 m^3/s

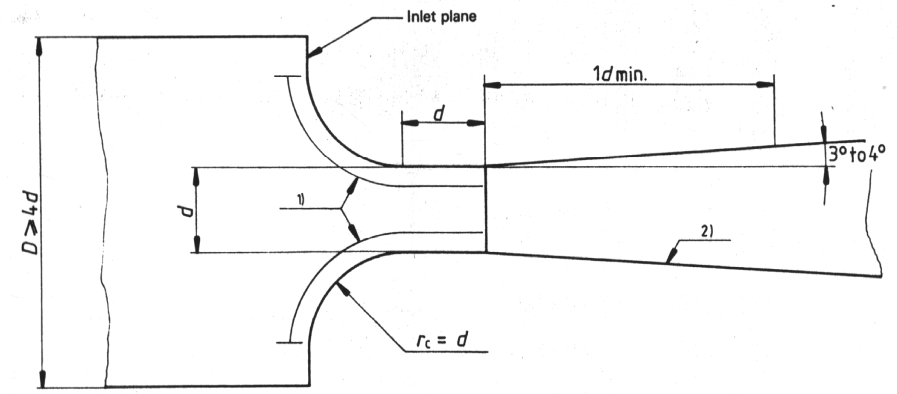

Figure 7. A drawing of a typical critical flow Venturi with a cylindrical nozzle throat [4]

Figure 7 is a technical drawing of a critical flow Venturi in accordance with standard ISO 9300:1990 (E). Figure 8 shows two photos of manufactured critical flow Venturi at the IMR Institute.

Figure 8. Two photos of a manufactured CFV: front view at the entrance to the nozzle (left), and side view at the Venturi nozzle (right) [9]

The difference between the calculated sizes of the CFV for two extreme cases is 2.8%, which results in a difference of 5.7% in the flow measurement, almost three times greater than the maximum error in flow measurement permitted by the ISO standards [2, 3] which is 2%. Estimates of CFV sizes using air or smoke gas data, inferred from the literature [4] – [7] lead to even greater errors. Thus, air or smoke gas data cannot be used for the calculation of a CFV for a dilution tunnel, especially for low dilution ratios. On the other hand, the case with a low dilution ratio (large engine, rated power) covers all expected regimes of the tunnel and these data are recommended for practical applications.

6. EXPERIMENTAL RESULTS

The manufactured full flow dilution tunnel with incorporated critical flow Venturi has been included in the existing system for the measurement of gaseous exhaust emissions. Several tests have been performed to check the dilution ratio and engine emissions. Some results of these tests are shown in Table 3 for various IMR diesel engines. These engines are the smallest units produed by IMR.

Engine emission tests were performed according to ECE Regulation No. 96 [3] using an 8-mode cycle [2]. Gaseous emissions were measured using analytical analysers: non dispersive infrared (NDIR) for CO, heated flame ionisation detector (HFID) for HC and heated hemiluminiscent analyser (HCL) for NOx. Particulates were measured by gravimetric method using filters for particle collection [12].

Table 3. The experimental results for diesel engine exhaust emissions, obtained using the new system [11]

Engine type	Swept volume	Net power	Diluted gas flow	Exhaust gas flow	Dilution ratio	NOx	CO	HC	PM
	dm^3	kW	m^3/h	m^3/h		g/kWh	g/kWh	g/kWh	g/kWh
M33	2.5	27.7	3187	157.3	19.3	8.092	4.443	0.935	1.332
M33	2.5	28.9	3205	161.4	18.9	7.837	5.753	1.077	1.241
M33/T	2.5	27.9	3219	160.7	19.1	5.033	3.110	0.938	1.451
DM33/T	2.5	32.6	3291	167.6	18.7	16.038	1.944	0.116	1.977
DM33/T	2.5	31.7	3223	151.1	20.3	15.810	2.655	0.318	2.133
DM33/TLP	2.5	33.3	3264	168.7	18.4	12.562	5.672	0.900	5.201
THDM33	2.5	40.4	3224	228	13.2	13.065	2.679	0.663	0.563
THDM33	2.5	40.2	3171	234.5	12.6	11.033	3.706	0.651	0.331
THDM33	2.5	40.9	3208	237.4	12.5	8.588	2.975	0.619	0.854
THDM33	2.5	42.1	3218	237.9	12.5	9.867	2.724	0.514	0.5.49
M34	3.33	39.6	3142	235.6	12.4	4.845	12.978	0.346	1.155

Measured diluted gas flow has been in the limits of approved critical flow Venturi and the dilution ratio was larger than the minimal permissible (4). The data shown in Table 3 for flows and dilution ratios are for rated speed. Thus, at lower engine speeds the dilution ratios are expected to be greater.

Since the tested engines are rather old, the levels of NOx and particulates PM emissions are very high and can reach only Stage II level [3]. The naturally aspirated 2.5 litre engine can meet Stage II only in the case of indirect injection (M33). Direct injection 2.5 litre engine can reach Stage II level only with turbocharging and intercooling (THDM33). A similar comment refers to the four cylinder 3.33 litre engines M34 and DM34.

The tests and measured emissions of particulate matters show that the manufactured system for exhaust gas sampling can be useful for studies of diesel engine emissions, especially of particulate matter (PM) emissions.

7. CONCLUSION

A design of a full flow dilution tunnel with a single dilution and CFV flow measuring device was realised based on the analysis of users needs and the analysis of technical solutions compatible with the ECE and ISO standards.

The design of the tunnel was carried out according to the appropriate standards for emission testing and standards for the measurement of gas flow by means of critical flow restrictors. The calculation of a CFV cannot be realised using only gas input data provided in the literature, due to the variations of gas physical and chemical properties during the emission tests. Data which were not provided in the literature were taken from numerous emission measurements performed at the IMR Institute.

The tunnel is designed in such a way that it provides modular upgrades according to the user's needs (double dilution, full automatisation of emission tests etc).

The tunnel is currently adjusted to the user's needs, but the engines of other manufacturers could be tested as well (this is the only full flow dilution tunnel in Serbia).

The new tunnel is expected to provide precise, accurate and repeatable diesel engine particulate emission measurements, which will contribute to progress in engine emission studies.

ACKNOWLEDGMENT

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КОНСТРУКЦИЈА ТУНЕЛА ЗА РАЗБЛАЖЕЊЕ ПУНОГ ПРОТОКА СА ВЕНТУРИЈЕМ КРИТИЧНОГ СТРУЈАЊА ЗА МЕРЕЊЕ ЕМИСИЈЕ ЧЕСТИЦА ДИЗЕЛ МОТОРА

Велимир Петровић, Злата Брацановић, Бранка Грозденовић, Стојан Петровић, Сергеј Сажин, Драган Кнежевић

На основу међународних стандарда, потреба корисника и захтева произвођача реализован је тунел за разређење издувних гасова. При конструисању тунела узет је у обзир низ ограничења дефинисаних у стандардима о контроли емисије и избору вентурија. Потребни подаци при дефинисању основног концепта тунела добијени су из бројних испитивања емисије обављених у Институту ИМР. У раду је такође приказан и краћи поступак прорачуна димензија вентурија критичног струјања. Посебна пажња је посвећена мерењу емисије честица користећи методу разређења издувног гаса, што не дозвољава коришћење једноставних термодинамичких и струјних параметара. Усвојен је метод одређивања емисије честица за два крајња случаја која се могу појавити током испитивања. Користећи резулате прорачуна конструисан је и израђен тунел за разблажење пуног протока са вентуријем критичног струјања који је затим испитан у Институту ИМР.