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SEPARATION OF PARTICULATE POLLUTANTS FROM THE EXHAUST OF INTERNAL COMBUSTION ENGINES BY A NOVEL SEPARATOR

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فصل الحبيبات الدقيقة العالقة بغازات العادم فى آلآت الأحتراق الداخلى باستخدام فاصل جديد

ملخص البحث

يعرض هذا البحث نتائج دراسة ميدانية تهدف الى بحث امكانية تعديل كاتم الصوت لمحرك احتراق داخلى يعمل بوقود الديزل بحيث يعمل فى نفس الوقت كفاصل للحبيبات الدقيقة الخارجة مع العادم أيا كان مصدرها أو نوعها. وفى هذه الدراسة تم التوصل الى ملامح وأبعاد أفضل كاتم للصوت يتناسب مع المحرك موضوع البحث و الذى باستخدامه فى نظام العادم للمحرك أمكن فصل أكثر من ٨٥ ٪ من الحبيبات الموجودة بالعادم دون أى تأثير ملموس على أداء المحرك.

ولم تتجاوز تكاليف هذا الفاصل تكاليف كاتم الصوت العادى (علبة الشكمان الخلفية) الا فى حدود ٥٠٪. كما أن قدرة هذا الفاصل على حجز الحبيبات الدقيقة لم تتاثر على مدى ٤٠٠ ساعة تشغيل مما يشجع على امكانية استخدامه فى الات الأحتراق الداخلى الديزل أو البنزين الثابتة منها أو المتحركة على السواء وذلك لفصل كم كبير من الحبيبات الملوثة للهواء بتكلفه زهيدة وكفاءة عالية.

ABSTRACT

This paper gives the results of a field study conducted to modify the tail muffler of an internal combustion diesel engine so that it can also acts as an efficient separator for the particulates present in the exhaust stream of that engine. The features of the best separator are it is able to remove over 85% of the particulates while its cost exceeds that of the usual tail muffler by only 50%. This separator did not cause remarkable effects on the performance of the test engine and its collection efficiency remained approximately constant over the test period (400 working Hours).

The obtained results suggest the possibility of modifying the tail muffler of any internal combustion engine so that it can also act as an efficient particulate separator at a very low expenses.

INTRODUCTION

The exhaust from internal combustion engines (ICE), either mobile and stationary is one of the major causes of air pollution. In the advanced countries air pollutants from ICE are more than 50% of the total air pollutants[1,2]. The major pollutants emitted by such engines are carbon monoxide, oxides of

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nitrogen, sulphur oxides, unburned hydrocarbons, and fine particulates or aerosols. Aerosols are composed of carbonaceous particulates resulting from inefficient combustion of fuels, oil droplets, lead compounds resulting from the use of tetraethyl lead in gasoline engines as about 75% of the lead present with burned gasoline is exhausted into the atmosphere while the rest is deposited inside the engine[2,3], phosphorus and zinc compounds resulting from the addition of zinc dialkyl dithiophosphate to the lubricating oil as a corrosion inhibitor which reaches combustion chamber past the piston rings and valve stem seals, barium; which is used as a smoke suppresser, fuel additives such as boron manganese, and nickel. A large fraction of these particulates lies in the range from 0.1 µm to 10 µm diameter. Because of their small size, these pollutants tend to remain suspended in a free floating state for long periods of time[4].

Due to the physical, chemical, and biological effects of such particulates they can cause a variety of harmful effects in the atmosphere, including lowering of visibility, effects on health; soiling; and synergistic enhancement of the effects other pollutants. Also, these particulates can form dense coherent deposits on the catalyst surface of the catalytic converters used to combate gaseous pollutants. Such deposits act as a diffusion barrier to exhaust gases and hence a reduction in catalyst activity occurs[5].

Efforts are being such to combate gaseous pollutants from internal combustion engines. Some of the measures which are adopted and are under investigation for the reduction of gaseous pollutants concentrations from internal combustion engines are: thermal reactors, catalytic exhaust reactors for the oxidation of hydrocarbons and carbon monoxide, catalytic exhaust reactors for the reduction of oxides of nitrogen, exhaust gas recirculation, and heterogeneous combustion. Some of these means are impracticable because they result in lowering the engine performance, and others are not economical[3,6,7].

Because effects of particulate pollutants are very complex and dangerous and their separation represent a removal of some kind of air pollutants at the same time preventing the foulding and hence deactivation of the catalyst of the catalytic converter that may be used to combate other gaseous pollutants present, studies directed towards removal of particulates from the exhaust of internal combustion engines are very important.

The aim of the present work is to modify a tail muffler of diesel engine so that it can also act as an efficient particulate separator to capture and separate as much as possible of the particulates present in the exhaust stream of the test engine. The used test engine is a Salavia Diesel Engine CKD PRAHA Type 2S 95A2 made in Czechoslovakia. This engine has two cylinders with air cooling. Its output is 15.4 Kw at 2000 rpm.

FEATURES OF THE SUGGESTED SEPARATOR

In view of the characteristics of particulates mechanical separators, successful particulates separator for the exhaust of internal combustion engines must fulfill the following requirements:

(1) It must collect as much as possible of the particulates present in the flowing exhaust stream.
(2) It must be connected directly to the present exhaust system minimum modifications.
(3) Its effects upon the performance of the test engine must be kept at minimum.
(4) Easy to fabricate at minimum expenses.
(5) Its working life must be equal to the working life of the remainder of the exhaust system.
(6) Its collection efficiency must remain constant over its working life.

As baffle separators are easy to fabricate at very low expenses, especially if the tail muffler of the test engine is modified to act as the required particulate separator; it was decided to modify the tail muffler of the test engine so that it can act as a baffle separator to capture and collect as much as possible of the particulates present in the flowing exhaust gas stream.

Modification of the tail muffler was conducted by inserting inclined baffles inside it. Some of these baffles were welded to the upper half of the muffler while leaving a certain space between their lower ends and the wall of the lower half of the muffler for the flow of the exhaust stream (baffle clearance). The remainder of these baffles (lower baffles) were welded to the lower half of the muffler leaving a certain space above them for the flow of the exhaust gas stream. Lower baffles were provided with an additional horizontal plate (2 cm in length) followed by another inclined portion to make a dead corner at the baffle-muffler connection, as shown in Fig.(1).

With such separator the anticipated separation mechanisms are a combination of internal forces, impingement, and gravitational settling. The dead corner was made to aid in trapping and capturing the particulates and to decrease the possibilities of the reentrainment of the separated particulates by the flowing exhaust stream. This provision can also direct the separated particulates onto its outer surface to settle inside the following dead corner.

The variables seem to affect the performance of the suggested separator are: number of baffles present which are determined by the muffler length and the baffle pitch, the inclination angle of the main baffle; the baffle width and hence the clearance between the baffle and the muffler wall (baffle clearance), inclination angle of the end portion of the baffle that makes the dead corner with the muffler wall; and the characteristics of the test engine.

In the present work the baffle pitch of upper or lower baffles was 12 cm. as the length of the tail muffler of the test engine was 50 cm. Decreasing this spacing below 12 cm. adds too much to the fabrication difficulties of the modified muffler. Such spacing produced three upper baffles and three lower baffles as shown in Fig.(1). For baffle clearance: baffles with clearances of 1/4 D and 1/3 D were tested, where D is the diameter of the cylindrical muffler. Baffles with three different inclination angles were tested, these angles were 30,45 and 60 degrees. The inclination angles of the end inclined portion of the lower baffles (dead corner) were kept constant at 30 degrees. while studying the effects of the previous mentioned variables upon the performance of the modified muffler. On reaching the test features of the modified muffler from the point of view of the baffle inclination angle and baffle clearance, the effect of the inclination angle of the dead corner upon the performance of the particulates separator was tested by using baffles with inclination angles of their dead corners of 30,20 and 10 degrees. Table (1) gives the main features of the tested modified mufflers.

Table 1 : The main features of the tested modified mufflers.

Symbol	Baffle clearance	Baffle inclination angle, degrees	Dead corner inclination angle, degrees
A	1/3 D	60	30
B	1/3 D	45	30
C	1/3 D	30	30
D	1/4 D	60	30
E	1/4 D	45	30
F	1/4 D	30	30
G	1/4 D	60	20
H	1/4 D	60	10

Each separator was provided with the suitable provision so that it can be connected directly to the test engine in the place of the tail muffler without any modification in the exhaust system of that engine. Provisions were also provided for the measurements of pressure drop across the separator and the temperature of the exhaust stream at the inlet and outlet of the separator. Figure (1) shows details of the modified muffler and a photograph for the test rig used in the present study.

MEASUREMENTS

The experimental work was devoted to study the effects of the modified muffler features and engine speed upon the amount of particulates removed from the exhaust. Variables which were studied include baffle clearance, baffle inclination angle, dead corner inclination angle and the speed of the engine.

Prior to each experimental run, the end of the tail exhaust pipe of the test engine was connected to a particulates collection arrangement in order to determine the mass of particulate laden by the exhaust stream. This arrangement was either a dry bag filter of a known mass made from woven cotton fibers (30 cm in length and 12.5 cm. in diameter) or a collection water tank (20-litre in capacity) made from 1 mm thick galvanized steel plate and half filled with water. This tank was provided with certain provisions for the entry and exit of the exhaust gas stream and water.

After the connection of the tested modified muffler (separator) in the place of the usual muffler and the particulate collection arrangement to the tail exhaust pipe, the engine was operated then its rotating speed was adjusted at the test value and left to operate for the specified test period.

Each separator was tested at 800, 1000, 1200 and 1500 rpm for 2 hours to get reasonable masses of particulates. During this period the required measurements of pressure drop the tail muffler, and the temperature of the exhaust stream before and after the separator were recorded at one hour interval. The amount of fuel consumed during each test was also measured. The engine was stopped at the end of the test period and the bag filter was dried at 105°C for three hours and weighed. The difference between the final dry mass of the bag filter and its initial dry mass gives the mass of the collected particulates. When using the water collection tank, water was filtered and the filter papers with the collected wet particulates were dried at 105°C for three hours and weighed to get the mass of the collected particulates. The average value of the two masses determined by the bag filter and the water collection tank was considered as the mass of particulates leaving with exhaust stream of the engine under the specified test conditions.

Preliminary tests were conducted by operating the engine with its usual muffler at the mentioned rotating speeds for the specified test periods to determine the amount of particulates present in the exhaust stream. Such data were needed for calculating the amount of particulates removed by each separator.

RESULTS AND DISCUSSION

Figure (2) gives the mass of particulates separated from the exhaust stream versus the operating time at the various rotating speeds of the engine. Particulates were separated from the exhaust stream through the use of either the bag filter (at rotating speeds below 900 rpm as at higher rotating speeds the bag filter was very soon torn) or the water collection tank described earlier. As anticipated more masses of particulates are separated at higher rotating speeds as higher rotating speeds means more fuel consumption and hence more particulates in the exhaust of the engine.

The mass of particulates separated from the exhaust of the engine can be expressed by the following empirical equation:

$$m = A \left(\frac{\omega}{1000} \right)^n t \qquad (1)$$

where: m : mass of particulates (in grams) separated during an operation period of t (hours), ω : rotating speed of the test engine (revolutions per minute, rpm) and A, n are constants seem to be dependent upon the load and the other characteristics of the engine and the properties of the used fuel. In the present study, all tests were conducted while the engine was unloaded. Values of A and n deduced from the experimental results are 1.27 and 1.5 respectively. Equation (1) correlates the experimental data within +5% .

Figure (3) gives a presentation of the particulates collection efficiency and pressure drop across the separator for the examined separators at the specified rotating speeds. Figure (4) and (5) illustrate the effect of the rotating speed of the engine and the effect of the baffle inclination angle as well as the baffle clearance upon the collection efficiency and the pressure drop for the six examined separators of which the end portion of the baffles (dead corner) has an inclination angle of 30°. These figures reveal the following :

1) The particulates separation efficiency decreases while the pressure drop across the separator increases with increasing engine speed. This is may be due to the fact that at higher speeds more fuel is consumed and hence more masses of particulates are emitted and carried by the flowing exhaust stream. Also, greater volumes of flue gases are exhausted which causes much disturbance to the flow patterns inside the separator. These finally exhaust stream and to entrainment of greater masses of particulates by this stream.

2) A noticeable increases in both the collection efficiency and the pressure drop accompany the decrease in the baffle clearance from 1/3 D to 1/4 D. The maximum recorded collection efficiency was 81% when the inclination angle of the baffle was equal to 60° with the engine running at 800 rpm the maximum pressure drop recorded was about 58 mm water when the inclination angle of the baffle was equal to 30° with the test engine running at 1500 rpm. These values were for separators having a baffle clearance of 1/4 D. This pressure drop is higher by about 18 mm water than that produced when the engine with the conventional tail muffler was tested at the same rotating speed. The noticed increases in both the collection efficiency and pressure drop are expected as smaller baffle clearances make the exhaust stream stays for longer times inside the separator with the possibility of more particulates separation by the separator and more back pressure exerting upon the flowing exhaust stream.

3) The pressure drop across the separator decreases while the particulates collection efficiency increases as the inclination angle of the baffle increases. As with more inclined baffles, sharp changes in flow direction take place to the exhaust stream on passing each baffle. This leads to flow separation behind each baffle which disturbs the flow patterns inside the whole separator causing the higher pressure drops around the separator and the greater masses of particulates entrained by the exhaust stream recorded with the decrease in the value of this angle.

4) For the separator in which the inclination angle of the dead corner was equal to 30°, separator D proves to be the best one from the point of view of both the particulates collection efficiency and pressure drop across the separator.

To study the effect of the inclination angle of the dead corner, two separators G and H which differ only from separator D in the value of that angle were fabricated and tested. This angle was 20 degrees in separator G while it was 10 degrees in separator H. Figure (6) gives the effect of the inclination angle of the dead corner of the baffle for separators D,G and H upon the particulates collection efficiency and the pressure drop through the separator. This figure shows that the collection efficiency increases while the pressure drop decreases with the decrease in the value of the inclination angle of the dead corner. This effect is more pronounced at higher rotating speeds. This can be attributed to the fact that with the decrease in the value of that angle, the end portion of the baffles becomes more longer so the flow of the exhaust stream over it becomes more streamlined with less chances for separation and disturbance of flow. Hence the back pressure exerted on the flowing exhaust stream is reduced. Also the dead corner acts as a trap in which the particulates settle quite with less chances for re-entrainned by the flowing exhaust stream.

In addition to the previous results Fig.(6) clearly reveals that separator H has the highest collection efficiency,followed by separator G then comes separator D at each one of the four studied rotating speeds. These three separators have almost the same pressure drop at 800 and 1000 rpm while at higher rotating speeds separator H has the lowest pressure drops. These date were for five hours operation period.

To study the effect of working life upon the performance of the suggested modified muffler, separators D,G and H were separately tested for 400 working hours. This was conducted by running the engine ten hours daily for 40 days. This adds no extra effect to the pressure drop across the separator while for separator D after ten days, from 20-30% reduction in the particulates collection efficiency were recorded in the first one hour of the operation period of each experimental run. However the efficiency is then rises to reach its higher value and remains constant over the rest of the operation period. This effect may be due to the detachment and entrainment of some of the particulates previously separated and adhered to the inside walls of the separator by the flowing exhaust stream. Separators G and H did not show such an effect (Fig.6). Measurements of average temperatures before and after the muffler for both usual or modified one show that the temperature of the exhaust stream was reduced by about 12°C when replacing the usual engine muffler by anyone of the tested modified mufflers. The cost of making separator H was 40 LE which is higher by about 50% than the cost of making the usual tail muffler of the test engine (about 25 LE).

The previous results and discussions indicate that separator H is the best separator suitable to simultaneously act as a tail muffler and a particulate separator for the internal combustion diesel engine used in the present study.

CONCLUSIONS

This paper presents the results of a field study conducted to modify the tail muffler of a two cylinder air cooled diesel engine having an output of 15.4 kW at 2000 rpm so that it can also act as a baffle separator to trap the particulates present in the exhaust of that engine before reaching the atmosphere.

The best features of the modified muffler were determined under actual working conditions. These include baffle clearance, inclination angle of main baffle and inclination angle of the dead corner, which are 1/4 D, 60°C respectively for the present study.

The best modified muffler was able to remove over 85% of the particulates present in the exhaust stream of the test engine while it had no remarkable effect on the performance of that engine. The temperature of the exhaust stream was decreased by about 12°C on passing the modified muffler. The fabrication cost of the modified muffler exceed that for the usual one by about 50% . After 400 working hours, no deterioration in the collection efficiency of the modified muffler was recorded.

Results obtained suggest the possibility of modifying the tail muffler of any internal combustion engine to act also as an efficient particulate separator at a very low cost. The best features of the modified muffler must be determined under actual working conditions.

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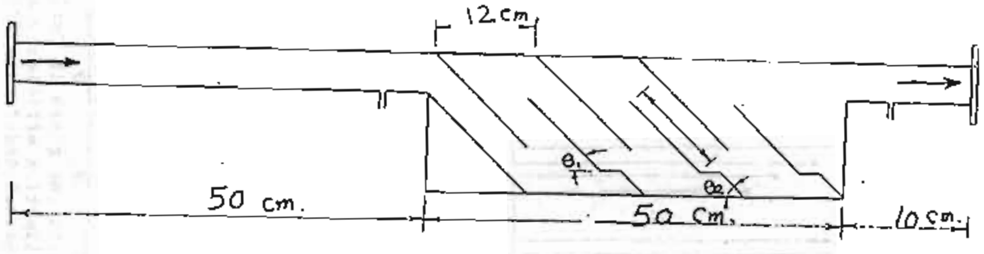
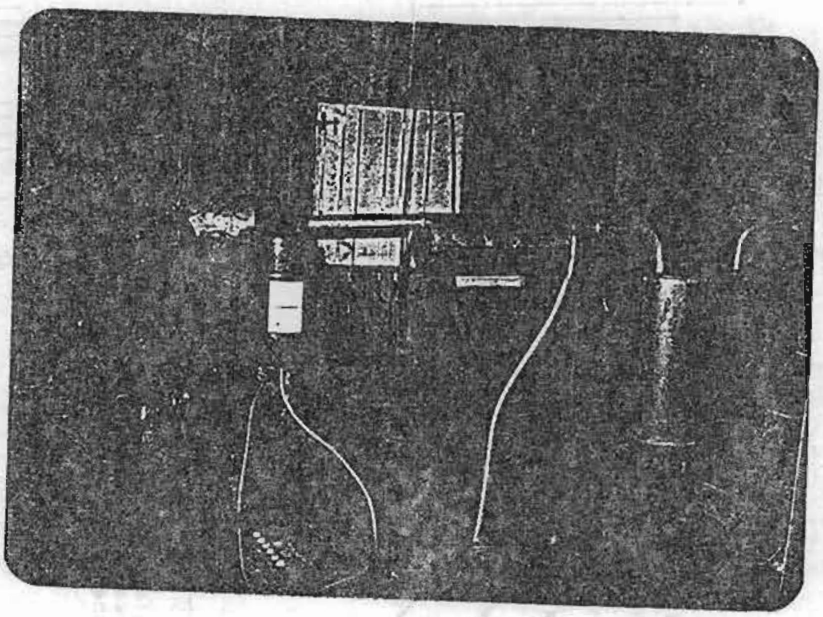
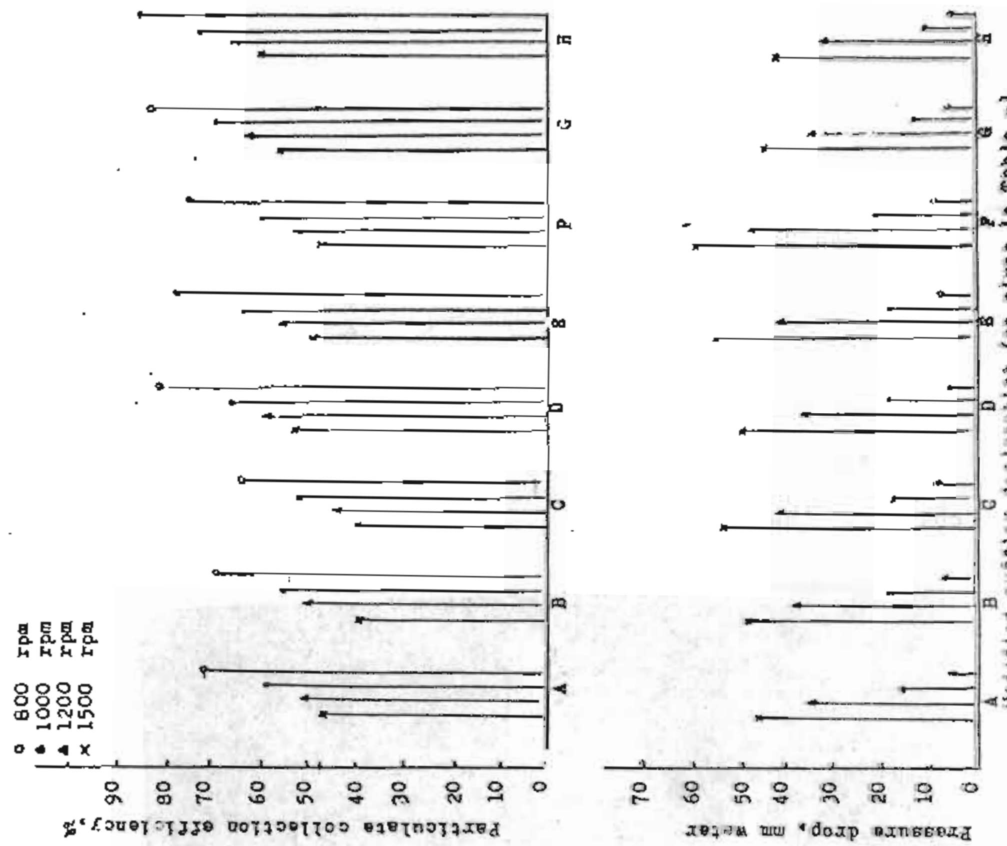


A sketch for the modified muffler
θ_1: inclination angle of the baffle, and θ_2: inclination angle of the dead corner.



A photograph for the test rig

Figure 1: A sketch for the modified muffler and a photograph for the test rig.



Modified muffler designation (as given in Table -1)
Figure 3: Particulates collection efficiency and pressure drop for the examined modified mufflers at the studied rotating speeds.

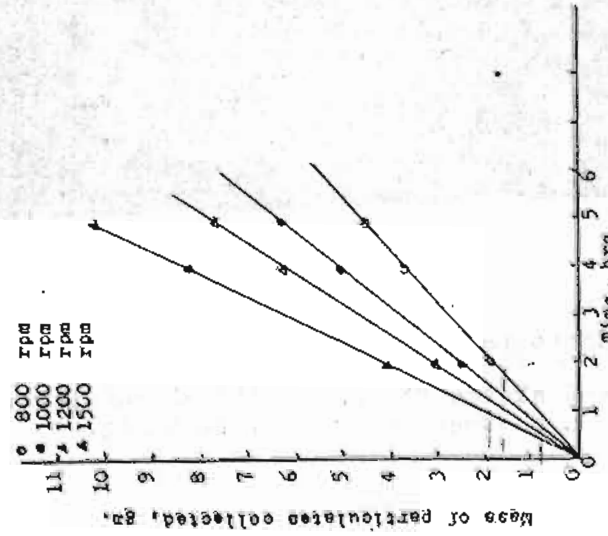


Figure 2: Mass of particulates separated from the exhaust stream of the test engine versus the collection time.

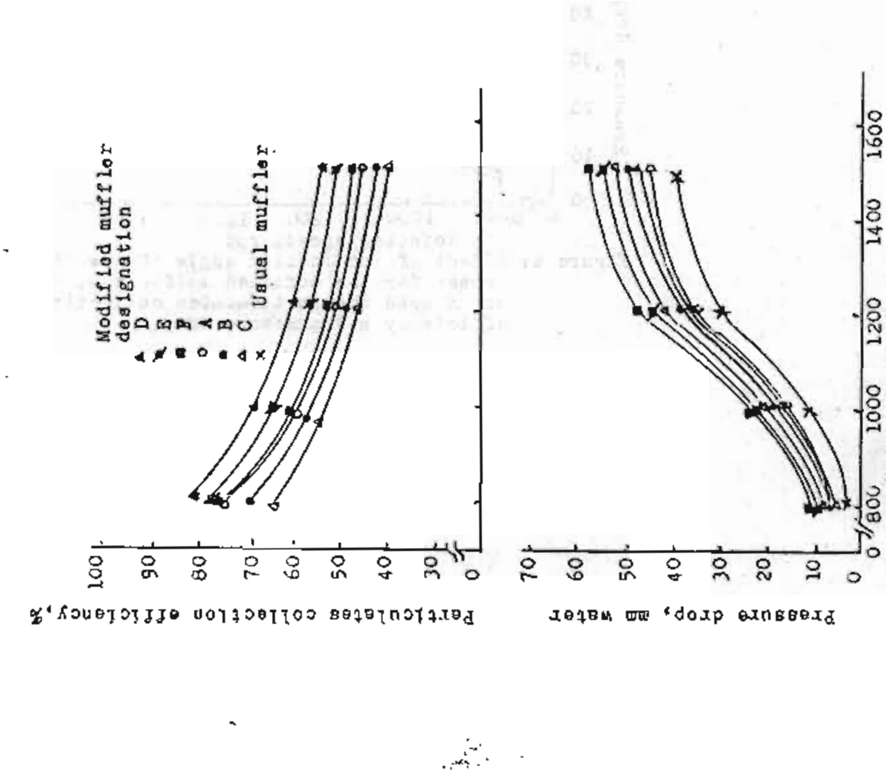


Figure 4: Effect of rotating speed upon the particulates collection efficiency and pressure drop for the modified mufflers A,B,C,D,E and F.

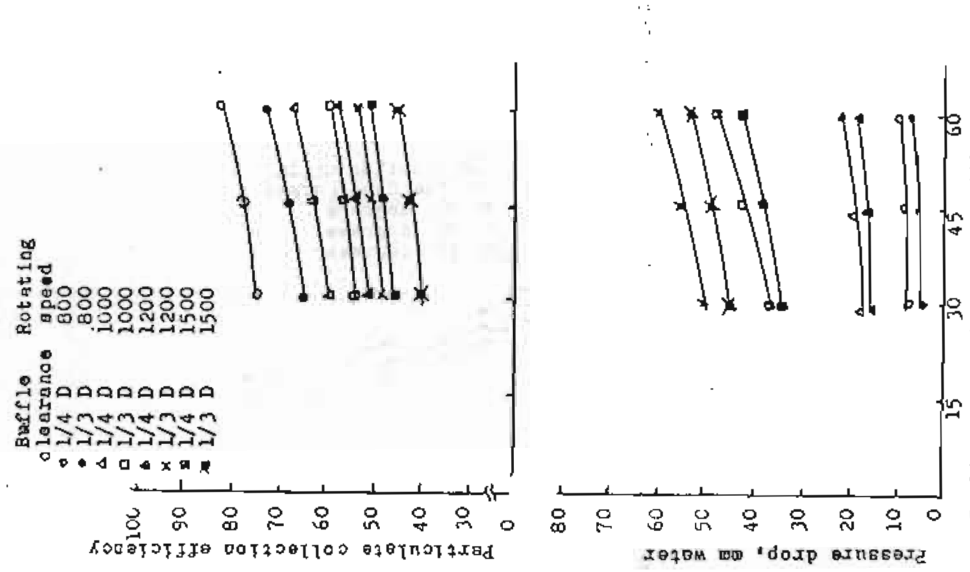


Figure 5: Effect of the baffle inclination upon the particulates collection efficiency and pressure drop around the examined modified mufflers.

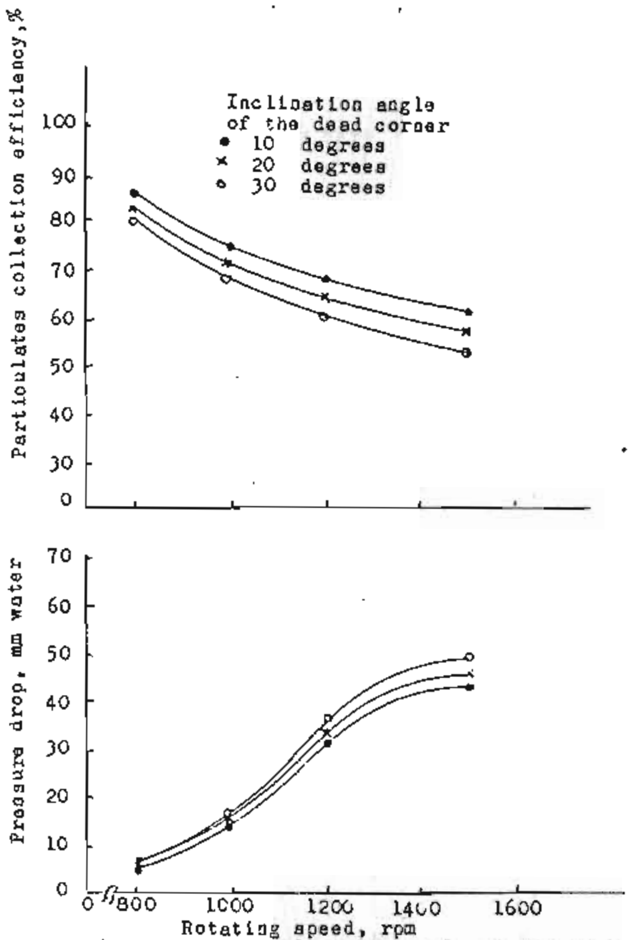


Figure 6: Effect of inclination angle of the dead corner for the modified mufflers D, G and H upon the particulates collection efficiency and pressure drop.