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EFFECT OF FLAME-TUBE HEAD STRUCTURE ON COMBUSTION CHAMBER PERFORMANCE

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This paper presents the experimental combustion performance of a premixed, pilot-type flame tube with various head structures. The test study covers an extensive area: efficiency of the combustion chamber, quality of the outlet temperature field, limit of the fuel-lean blowout, ignition performance at ground starting, and carbon deposition. As a result of these tests, a nozzle was found which fits the premixed pilot flame tube well. The use of this nozzle optimized the performance of the combustion chamber.

The tested models had premixed pilot chambers with two types of air-film-cooling structures, six types of venturi-tube structures, and secondary fuel nozzles with two small spray-cone angles.

INTRODUCTION

After a period of engine operation, a premixed pilot-type flame tube (fig. 1) with a pressurized fuel nozzle may have difficulty in starting. Sometimes the pilot chamber may not ignite at all; this seriously affects the starting performance of the engine. This problem is generally believed to be due to carbon deposition in the premixed pilot chamber (8 g carbon deposited in a single premixed pilot chamber after 190 min of running). In the case of high-load running, the gas temperature in the center of the premixed pilot chamber can be raised as high as 1200 °C; this can make the high-density fuel spray crack and deposit on the downstream section of the nozzle. In addition, the wall temperature would be high, causing the fuel spray to form coke on the wall, which (coupled with fuel deposition) would make the wall rough. Then the carbon particles would hit the cores of deposition and would be deposited on the wall. Thus, the wall becomes uneven and very rough. When the fuel spray again hits the wall and flows on its uneven soft carbon layer, the fuel film is also very uneven (unlike the film on a smooth metal wall). As a result, the spray quality becomes very poor and the engine fails to start.

The objective of this experiment was to improve the ground starting performance while not damaging the other types of combustion performance. The study concentrated on the effect of premixed pilot chamber structures and nozzle spray angles on combustion performance.

This paper presents a study of the effect on combustion of (1) premixed pilot chambers with air-film-cooling and venturi-tube structures and (2) small-angle secondary nozzles. It emphasizes their effects on ground starting performance and on carbon deposition within the pilot chambers.

TEST MODELS

Premixed Pilot Chamber With Air-Film-Cooling Structure

It is known that the air-film-cooling structure enables free carbon particles to be carried away by the film-cooling air flow, thus reducing or avoiding the contact of these particles with the wall. This helps reduce the wall temperature. Two models were evaluated (fig. 2). Eighty film-cooling holes (ϕ2) were added to the wall of these two premixed pilot chambers. The ratio of the cooling-hole opening area to the total opening area in the flame tube wall was 0.022. The air velocity in the outlet of the air-film-cooling ring was 15 to 26 m/sec.

Premixed Pilot Chamber With Venturi-Tube Structure

A venturi tube was mounted in the rear of the swirler (fig. 3). It made the fuel injected from the nozzle hit the venturi-tube wall and then mix with the air coming from the inner section of the swirler, thus avoiding contact of the fuel with the flame tube wall. In addition, because the venturi tube was used, the position of the recirculation zone moved further downstream of the nozzle; as a result, the temperature of the carbon-generating zone downstream of the fuel nozzle was reduced. This helped reduce the carbon particles.

Six venturi tubes of different sizes were evaluated. (See table I and fig. 4.) The ratio of the outer to the inner area of the swirler was 1.16 when the venturi tube was mounted.

Secondary Nozzle With Small Spray Angle

Fuel entered from the centrifugal nozzle in the ignition process in order to reduce or eliminate the probability of the sprayed fuel hitting the wall. Two kinds of small spray-angle secondary nozzles were studied. (See table II and fig. 5.) The spray angle was made small enough that the spray would not hit the inner wall of the premixed pilot chamber. Thus, the fuel spray cone was not impaired. The fuel-air ratio was appropriate near the ignitor, and a good starting performance was maintained (even if there was carbon deposition in the pilot chamber).

RESULTS AND ANALYSIS

Amount of Carbon Deposition in Premixed Pilot Chamber

The experimental results for various models are listed in table III. (Results for the original flame tube are included for comparison.) The results indicate that the venturi tube is the best structure for eliminating carbon deposition. There was almost no carbon deposition in the pilot chamber, and there was only a small amount of carbon deposition in the 20- to 30-mm position downstream of the pilot chamber exit. The objective of reducing carbon deposition in the pilot chamber was achieved.

Results from the water analog test indicate that there was no recirculation zone in the venturi tube. The recirculation zone in the premixed pilot chamber was located far downstream of the nozzle (fig. 6). The heat radiation from the flame-tube center to the nozzle was blocked outside of the venturi tube, thus reducing the temperature downstream of the nozzle. This had a determinate effect on the reduction of the carbon particles. It was for this reason that the amount of carbon deposition in the flame tube with a venturi tube was obviously reduced.

Adding an air-film-cooling structure in the premixed pilot chamber helped reduce carbon deposition. The reduction rate was usually as much as 20 to 30 percent near the air-film exits. But, at the exits of the air films, the air velocity was small, so was the air-flow momentum. Nevertheless, the momentum of the fuel injected from the nozzle was rather large, so the film flow could not prevent the fuel droplets from hitting the wall. It is only possible for the film air to bring away free carbon particles. For this reason, this structure is not very effective in reducing carbon deposition.

Ground Starting Performance

The results for five models at the ground starting ignition condition are shown in figures 7 and 8 where V_2 is the inlet velocity of the combustion chamber. The curves of figure 7 indicate that there is an optimal value for each curve. This velocity ranges from 15 to 20 m/sec. The ignition performance was best for the flame tube with a model I venturi tube.

Figure 8 indicates that the ground starting ignition performance improved greatly when model I and II nozzles were used under carbon deposition conditions in the premixed pilot chamber. At 17.5 m/sec of inlet velocity the fuel-lean ignition limit improved; the limiting air-fuel ratio increased from 36.8 to 63.2. It is readily seen from these results that, under the carbon deposition condition in the premixed pilot chamber, adoption of a small-angle secondary nozzle obviously improves the ground starting ignition performance.

In addition, it is known from the curves that when carbon is deposited in the premixed pilot chamber the air-fuel ratio of the fuel-lean ignition limit decreases from 47 to 36. This confirms that carbon deposition in the premixed pilot chamber deteriorates the ground starting ignition performance.

Outlet Temperature Field of Combustion Chamber

Table IV shows the test results of various venturi-tube models. It is readily seen from the table that the size of the venturi tube mounted in the premixed pilot chamber has a great effect on the combustor outlet temperature field. The outlet temperature distribution factor (OTDF, table IV) of the model V combustion chamber was 0.155; this was much better than that for the original model (0.229). The OTDF's of models I and II were similar to that of the original model, but those of models IV and VI were inferior to that of the original model.

The convergent angle of the front section and the outlet angle of the venturi tube have an obvious effect on the combustor outlet temperature distribution. When the convergent angle of the front section of the venturi tube increases, the uniformity of the combustor outlet temperature field decreases. When the convergent angle was increased from 27°34' to 67°22', the OTDF increased from 0.209 to 0.301. When the venturi-tube outlet angle became rather small, excessive fuel concentrated in the center of the flame tube; this caused the temperature to rise in the center region and the outlet temperature distribution to deteriorate. For example, reducing the outlet angle of the venturi tube from 88° to 56° increased the OTDF from 0.155 to 0.301.

Adoption of a secondary nozzle with a small spray angle also improved the uniformity of the combustor outlet temperature field - the OTDF of model II was 0.175, the radial temperature distribution factor (RTDF, table IV) was 0.077.

Stability of Combustion Chamber

Figure 9 shows experimental results of the fuel-lean blowout limit for various models. The shapes of the curve are nearly the same for various models. The fuel-lean blowout limit for the model II venturi tube was wider because this venturi tube had no throat section; thus, a small recirculation zone was formed inside the venturi tube. The size of the recirculation zone was limited to the nozzle diameter range (fig. 10).

The fuel-lean blowout limits of the model III, IV, and V venturi tubes were narrower. It is known from water analog test results that there is a high-speed rotating flow in the throat section of a venturi tube (fig. 11). This unstable flow deteriorates the fuel-lean blowout limit.

When a secondary nozzle with a small spray angle was adopted, the fuel-lean blowout limit improved in the wide velocity range.

CONCLUSIONS

This study led to the following conclusions:

(1) Adoption of the secondary nozzle with a small spray angle not only solves the engine's starting ignition problem when there is carbon deposition in the premixed pilot chamber but also extends the ground starting ignition range and improves the uniformity of the combustor outlet temperature field.

(2) Adoption of an air-film-cooling structure reduces the amount of carbon deposition on the wall of the premixed pilot chamber. But since there is only limited cooling air available, it is not easy to totally eliminate the carbon deposition in the premixed pilot chamber.

(3) Mounting the venturi tube in the rear of the swirler is effective in eliminating carbon deposition in the premixed pilot chamber. But the geometry of the venturi tube affects the uniformity of the combustor outlet temperature field and the ground starting ignition performance; therefore, characteristic geometric parameters of the venturi tube have to be elaborately adjusted.

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TABLE I. - CHARACTERISTIC DIMENSIONS OF VENTURI TUBE

Model	Inlet Diameter, mm	Length, mm	Throat diameter, mm	Outlet cone angle, deg	Outlet diameter, mm
I	42	36	30	56°	40
II		25	42	36°32'	45.3
III		25	30	56°	40
IV		20	30	56°	35
V		20	30	88°	40
VI		15	15	0°	15

TABLE II. - CHARACTERISTICS OF NOZZLE

Model	Spray angle, α_{sec}, deg	Fuel flow, $G_{f_{sec}}$, liter/hr	α_{double}, deg	$G_{f_{double}}$, liter/hr
	Fuel supply pressure, $P_{T_{sec}} = 10$ kg/cm^2		Fuel supply pressure, $P_{T_{double}} = 30$ kg/cm^2	
Original	91	24.6	103	602.4
I	51	24.6	100	602.4
II	62	23.16	100	593.4

TABLE III. - EFFECT OF VARIOUS MODELS ON CARBON DEPOSITION

[Test conditions at inlet of combustion chamber: air pressure, P_2^*, 6 kg/cm^2; air temperature, T_2^*, 595 K; air flow, G_a, 3.135 kg/sec; air-fuel ratio, a/f, 70; test duration, 2.5 hr.]

Model	Amount of carbon deposition, g	Relative percentage
Original flame tube	1.3	100
Model I venturi tube	.072	5.54
Model VI venturi tube	0	0
Model I air film cooling	1.076	82.8
Model II air film cooling	.932	71.7

TABLE IV. - EFFECT OF VENTURI-TUBE GEOMETRY ON PERFORMANCE OF COMBUSTION CHAMBER

[Test conditions at inlet of combustion chamber: air pressure, P_2^*, 6 kg/cm^2; air temperature, T_2^*, 695 K; air flow, G_a, 3 kg/sec; air-fuel ratio, a/f, 52.2.]

Model	Original	I	II	III	IV	V	VI
Inlet convergent angle	-----	27°34'	-----	62°	67°22'	67°22'	122°
Outlet cone angle	-----	56°	-----	56°	56°	88°	-----
[a]OTDF	0.229	0.209	0.223	0.236	0.301	0.155	0.406
[a]RTDF	.083	.143	.098	.133	.138	.085	.110
[a]η_c	.984	.984	.975	.988	.997	.979	.929

[a]OTDF = $(T^*_{3_{max}} - T^*_2)/(T^*_{3_{av}} - T^*_2)$; RTDF = $(T_{3_{max(h)}} - T^*_2)/(T^*_{3_{av}} - T^*_2)$; and η_c = efficiency of combustion chamber where $T^*_{3_{av}}$ is the average combustion outlet temperature, $T^*_{3_{max}}$ the maximum combustor outlet temperature, and $T^*_{3_{max(h)}}$ the maximum combustor outlet temperature along the blade height.

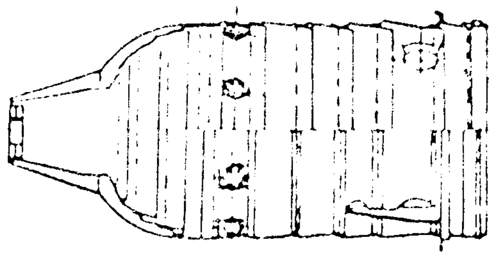


Figure 1. - Flame tube with premixed pilot chamber (original model).

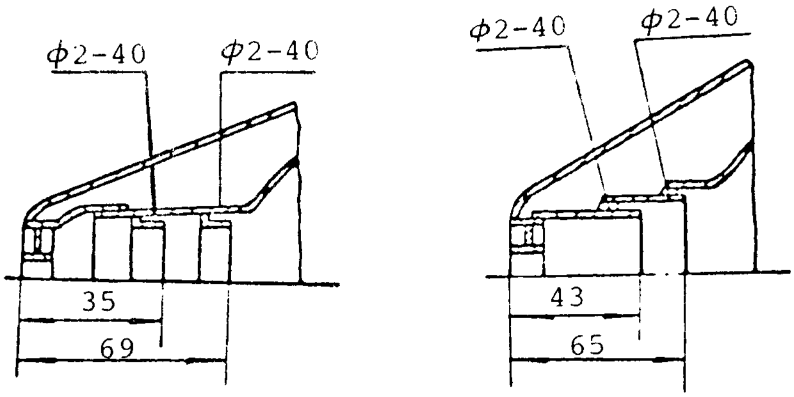


Figure 2. - Scheme of air-film-cooling structure. (See table I.)

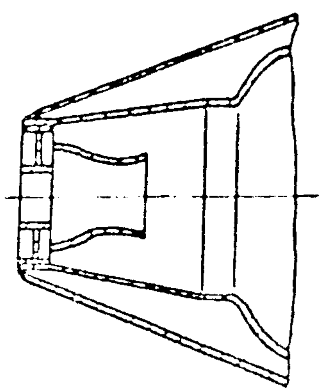
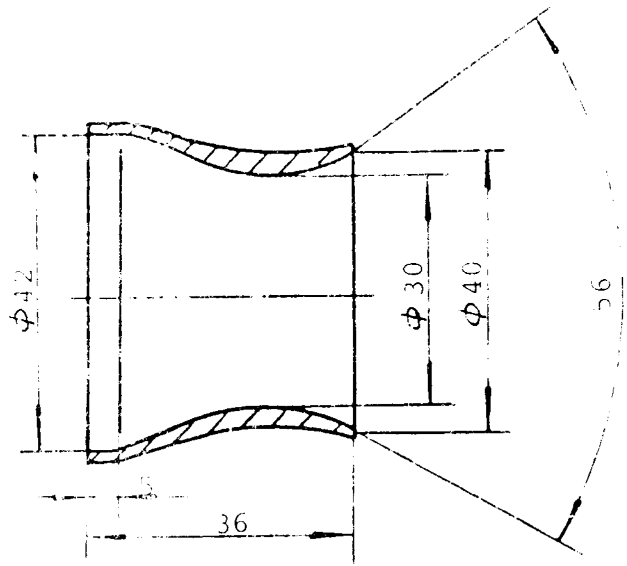
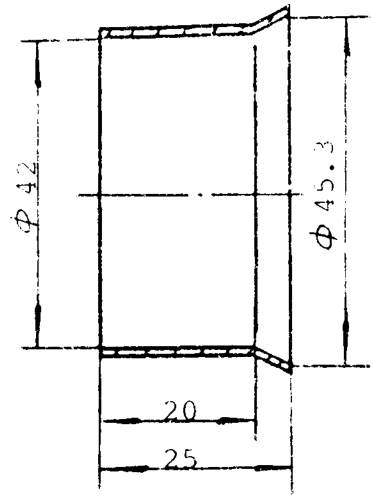


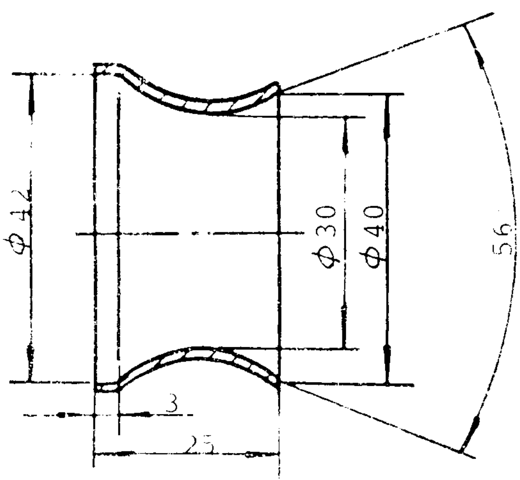
Figure 3. - Scheme of head of flame tube with venturi tube.



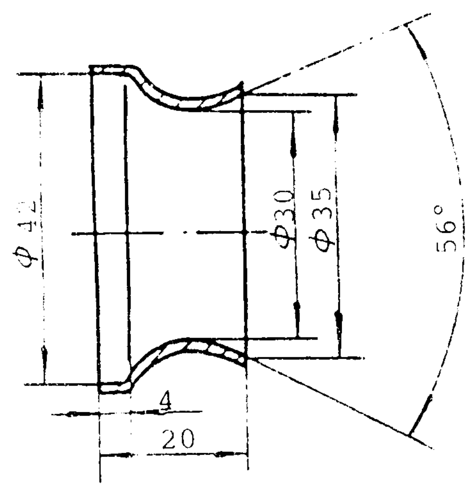
(a) Model I.



(b) Model II.

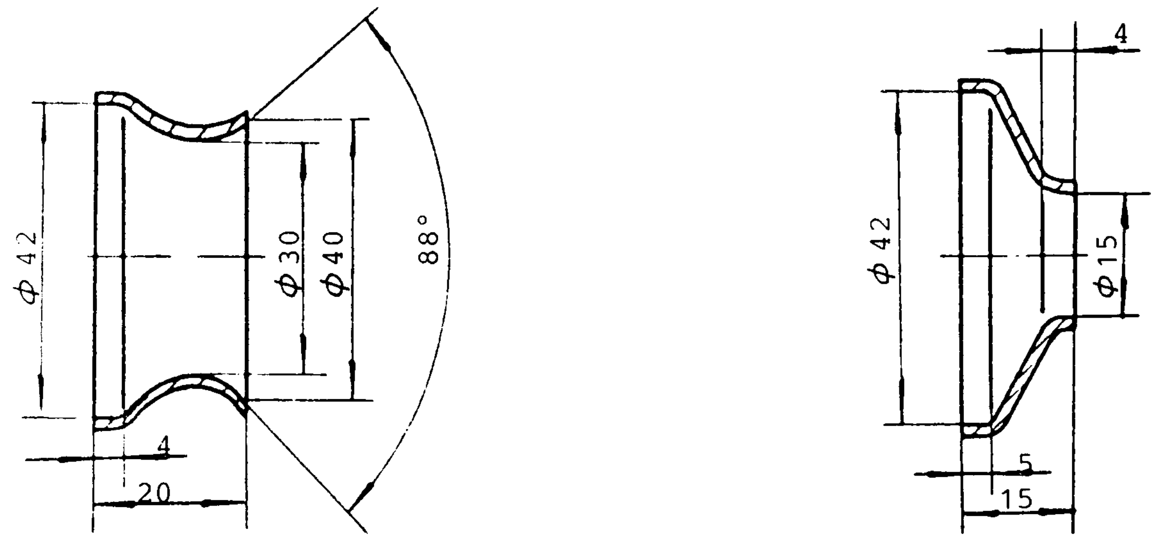


(c) Model III.



(d) Model IV.

Figure 4. - Structures of venturi-tube models I to VI.



(e) Model V.

(f) Model VI.

Figure 4. - Concluded.

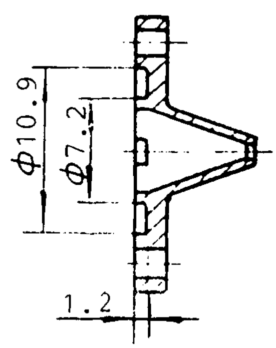


Figure 5. - Secondary nozzle.

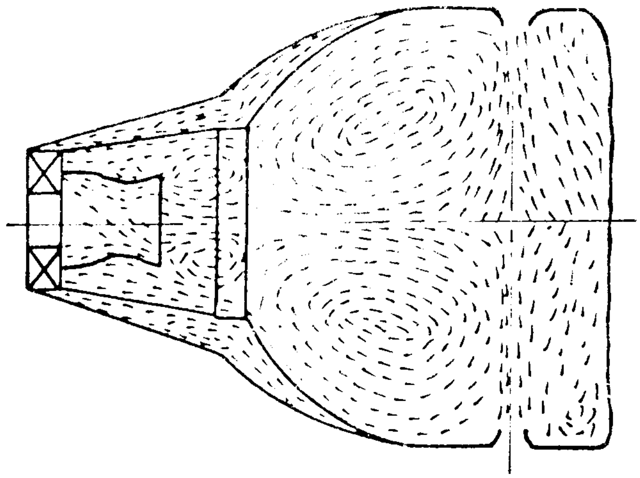


Figure 6. - Flow spectrum in flame-tube head with model I venturi tube.

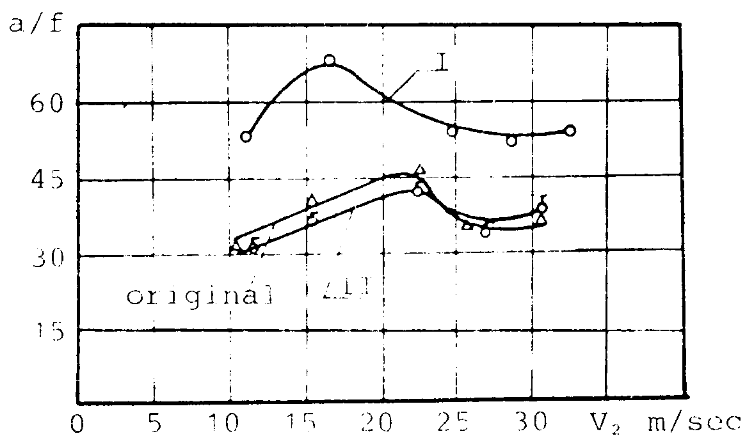


Figure 7. - Effect of venturi-tube size on ground ignition performance. Test conditions at combustion chamber inlet: air pressure, P_2^*, 1.04 kg/cm^2; air temperature, T_2^*, 331 K.

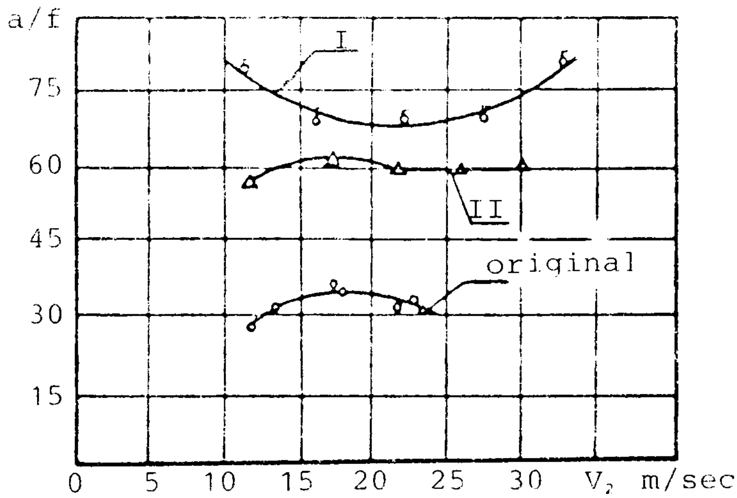


Figure 8. - Effect of fuel spray angle on ground ignition performance with carbon deposition in premixed pilot chamber. Test conditions at combustion chamber inlet: air pressure, P_2^*, 104 kg/cm^2; air temperature, T_2^*, 311 K.

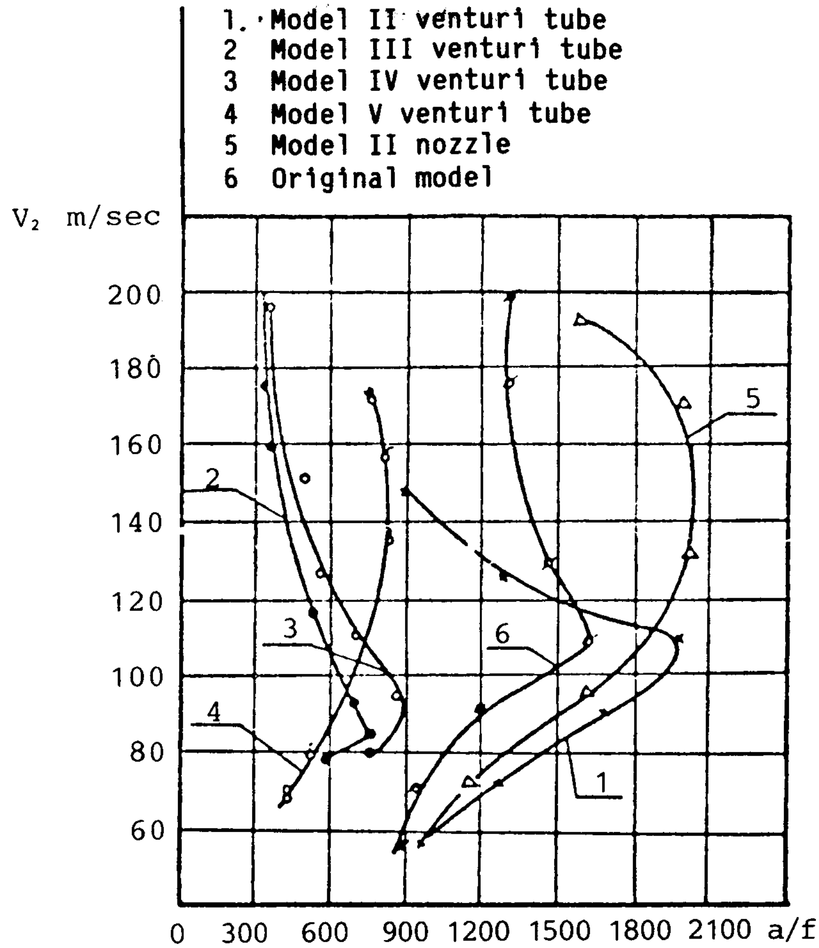


Figure 9. - Fuel-lean limits of various models. Test conditions at combustion chamber inlet: air pressure, P_2^*, 4.75 kg/cm^2, air temperature, T_2^*, 655 K.

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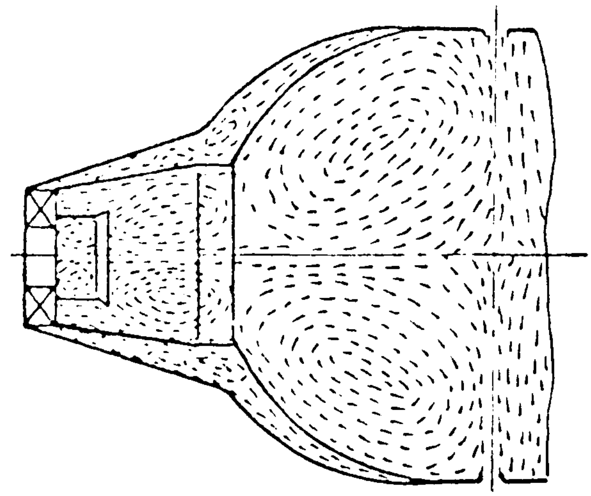

Figure 10. - Flow spectrum in flame-tube head with model II venturi tube.

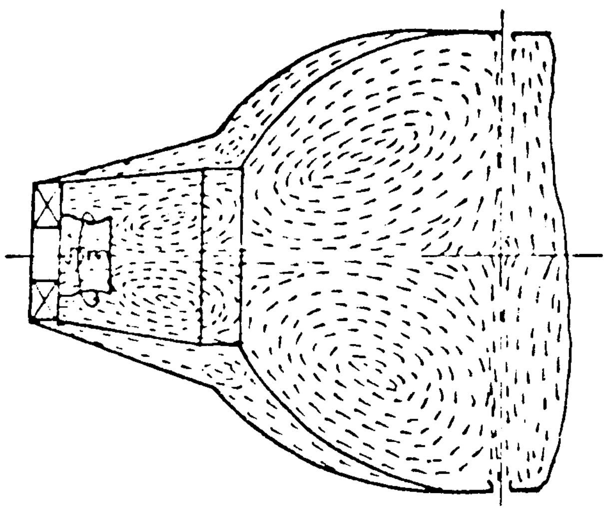

Figure 11. - Flow spectrum in flame-tube head with model III venturi tube.