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The Combustion Characteristics of a Cylindrical-Rod Burner System *

-by-

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SUMMARY

Combustion systems constructed of a multiplicity of small elements appear attractive from the aspects of low pressure loss and short chamber length. A combustion chamber has been proposed, by Spalding of Cambridge University, in which fuel is fed under gravity down the surfaces of vertical cylinders located normally to the air stream. Preliminary tests were made at Cambridge, and the work has been continued at Cranfield under a Ministry of Supply Contract.

The cylindrical rod elements have been tested in both open and closed type chambers, a polished rod of 1/8in. diameter giving the best performance of the rods tested. Single and double row grids have also been tested, and the results have been extended theoretically to give a comparison with the performance of a conventional type of spray chamber operating at similar inlet conditions.

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* This report is based on sections of a thesis submitted by Mr. J.J. Eden in June, 1952 (ref. 8), and a thesis submitted by Mr. T.J. Croysdale in June, 1953 (ref. 9), as part of the requirements for the award of the Diploma of the College of Aeronautics. The report also includes notes on further work undertaken by Mr. J. Gallichan, the project being under the overall supervision of Mr. E.M. Goodger.

It is found that satisfactory combustion of kerosine can only be established over a narrow range of fuel flow for each air flow, and that the maximum air speed before extinction is, at present, no higher than 70 ft./sec. The combustion intensity is reasonable in value but is localised, with a very high air/fuel ratio and a poor temperature distribution near the flames. Increasing the number of rows of rods leads to overheating troubles with the downstream rows. The combustion efficiency falls off markedly due to separation of droplets as the extinction speed is approached. It is concluded that cylindrical rods are unsatisfactory as elemental burners for a high performance chamber, but further development of porous burner elements of non-circular section, fed internally with fuel under pressure, may be worthwhile. Difficulties may be experienced due to blockage by fuel-borne solids and by the formation of carbon on the downstream surface of the elements.

CONTENTS

1. Introduction

The literature records the use of cylindrical rods placed in fuel-air streams for purposes of initiating combustion (ref. 1), and for stabilising flames (ref. 2). The work of Spalding at Cambridge University (ref. 3), which has been directed mainly towards the physical phenomena of mass and heat transfer, included the burning of liquid fuel on the surface of vertical cylinders located normally to an airstream. Spalding's proposal was a combustion system in which the fuel remains fixed in space and the air moves past, thus avoiding the extensive turbulence required with spray atomization to prevent fuel droplets leaving the chamber before completing combustion.

The early results from Cambridge indicated that liquid fuel can be burnt on a cylindrical rod with a short blue open-wake flame, involving only very small pressure loss, the optimum rod diameter being 1/8in. This work has been continued at Cranfield under a Ministry of Supply contract in order to make a practical assessment of the performance of a multi-rod system, and a comparison with the performance of a conventional type of chamber operating at similar inlet conditions.

The preliminary Cambridge tests were made in an open chamber, i.e. with a single rod fitted at the end of an air duct. A similar rig was first used at Cranfield, in order to correlate with the Cambridge results, and to determine optimum conditions for subsequent application to multi-rod burning. The variables investigated included rod diameter, fuel flow, air flow, Reynolds number, surface finish and form, fuel temperature, and air temperature. A closed section chamber was then used, and the results for single and double banks of five rods were compared with those from a Derwent I. chamber tested at similar inlet conditions. The Cambridge investigations covered a range of hydrocarbon fuels, but work at Cranfield has been confined to D.Eng.R.D. 2482 kerosine.

2. Apparatus

2.1 Combustion Chambers

The preliminary tests were made in the open chamber shown in fig. 1. The air was supplied through an 18in. settling length of 5in. x 6in. duct into a 3in. traversing length fitted with a thermometer, a wall pressure tapping, and a pitot traverse gear. The burner rod was fitted at the open end of the traversing section, and an exhaust collector duct and fan were provided to lead the combustion products away to atmosphere. A typical flame obtained with a single rod in an open chamber is shown in fig. 2.

The early type of closed chamber was constructed from mild steel angle and sheet, but the internal flow resistance was high, and the flexibility of the chamber roof made it difficult to prevent fuel leakage outside the chamber. The final type of closed chamber, shown in figs. 3 and 4, comprised one piece of 16 S.W.G. mild steel sheet, bent to shape and welded along the seam. The burner manifold was mounted on a flat transverse stiffening plate brazed to the top of the combustion chamber, and was sealed by a compressed cork gasket. The fuel collector and drain was clamped and sealed to the underside of the chamber in the same way. The windows fitted to permit observation of the flames were hinged to allow insertion of the ignition torch.

2.2 Burner Rods

The greater part of the investigation was carried out with brass rods of 1/8in. diameter, and some final tests with rods of mild steel and stainless steel. No other materials were tested. Fig.5 illustrates the complete range of rods used.

2.3 Air Supply

The air was supplied from an Allis Chalmers rotary-vane water-cooled compressor driven by a 125 h.p. induction type electric motor. After passing through an oil separator and a surge tank, the air was led through a hand-operated gate valve, and, through a filter and smoothing section, into the 18in. settling length. Excess air could be blown off to atmosphere.

2.4 Fuel System

In the fuel system shown in fig. 6, fuel was pumped from the main tank to the constant-level header tank by a 24-volt D.C. aircraft type of fuel pump. The overflow was returned to the pump inlet, and the supply to the burner manifold, under a head of about 3 ft., was controlled by cock 'A'. From the manifold, fuel was metered to the individual rods by hand-controlled needle valves. Fuel drained from the rods was collected in a measuring tube, the return flow being controlled by cock 'B'. The vapour trap consisted of a thimble of fine mesh cotton gauze wired onto the end of the return pipe.

A cock 'C' was fitted in the pump feed line, so that the fuel contained in the measuring tube could be isolated from the main supply. The fuel consumption was measured as a drop in fuel level in the tube over a timed interval. The first tests in a closed combustion chamber were made with a re-circulating fuel system, but for the later tests the fuel from the rods was drained separately. This practice was adopted to ensure that fuel with the same volatility was used for all tests.

The method of feeding fuel to the rods is shown in detail in fig. 7.

2.5 Instrumentation

Provision was made for traversing a 2 mm. pitot tube across the whole of the inlet area in the 3in. length traversing section. The tube could slide vertically in a hole through a horizontal plate, which was in turn allowed to slide horizontally in guides fixed across the top of the tunnel. Static pressure was taken from a tapping in the tunnel side wall, and a vertical Chattock manometer was used to measure total head, static pressure, or pressure differences, to within 0.001 in. of water. A similar traversing section was fitted at the outlet of the closed chamber, and traverses could be made with either a pitot tube or a shielded chromel-alumel thermocouple in planes 8in., 12in., and 17.5in. downstream from the first row of rods. A Cambridge portable potentiometer was used for measuring the thermocouple output to within 0.01 millivolts. The air inlet temperature was measured by means of a mercury-in-glass thermometer inserted into the airstream 10in. upstream of the burner rods. The fuel temperature was read from a mercury-in-steel instrument, of 0 to 160°C range. For certain tests with a 3/8in. diameter hollow steel rod, the rod wall temperature was measured by means of a chromel-alumel thermocouple peened into a small hole drilled through the rod.

2.6 Test Procedure

The following procedure was adopted.-

a. The fuel pump was switched on and a steady overflow rate set from the constant head tank.

b. The air exhaust fan, the cooling water circulating pump, and the Allis Chalmers compressor were switched on in turn.

c. When the air inlet temperature reached about 30°C, the main fuel cock to the burner grid was opened, and the needle valve over each rod adjusted to give sufficient fuel for lighting up.

d. With the air velocity set to about 10 ft./sec., the asbestos-wound igniter torch was dipped into methylated spirits, lit by means of a magneto spark, and applied to the rods to ignite the fuel.

e. The air and fuel flows were set up to the required values, and conditions allowed to become stable before readings were commenced.

All the tests were performed with inlet conditions of approximately 1 atmosphere and 40°C. The kerosine was unheated before inlet to the chamber except during those experiments expressly intended to show the effects of variation in fuel temperature. The manometer and potentiometer were set to zero whilst disconnected from the rig.

3. Experimental Results

3.1 Tests with a Single Rod

Investigations were made over fairly wide ranges of most controlling factors of operation, and optimum conditions were considered to hold when a blue open-wake flame could be established along the whole length of the rod. In general, these conditions were found to lie within comparatively narrow ranges and could only be obtained by fine adjustment and visual observation of the flame. The following paragraphs on the effects of the operating factors apply to a single brass rod of 1/8in. diameter fitted at the end of the open chamber.

3.1.1 Influence of Air Inlet Conditions

At very low air speeds, a bright luminous flame was established enveloping the whole of the rod and greatly elongated in the stream direction. The flame was maintained by vaporization from the fuel surface due to the flow of air, and of heat from the flame. The pressure differences around the cylinder at this velocity were insufficient to overcome the film energy of the fuel, and this flowed steadily over the whole surface of the rod.

As the air speed was increased, a value was reached at which the increased pressure at the front stagnation point caused the fuel to be pushed into the low pressure regions on the sides, and only the flame in the region of the wake remained. At an air speed of 6 ft./sec., this luminous region in the wake was bounded by two short sheets of blue flame near the junction of the luminous flame and the rod surface. As the speed further increased, the luminous region was shortened and the blue bounding flame gained in strength and length. At 10 ft./sec., the central wake flame was completely extinguished, leaving an open wake flame of two symmetrical blue sheets.

At 40 ft./sec., the fuel film at the lower end of the rod had insufficient momentum to resist the viscous forces of the air flow, and droplets of fuel were torn off and carried downstream burning with a yellow flame. With further increase in air speed to 50 ft./sec. ($Re = 2.7 \times 10^3$ based on rod diameter) the droplet separation spread progessively up the rod. Eventually a critical speed was reached at 70 ft./sec. ($Re = 3.9 \times 10^3$)

at which both symmetrical flames were blown downstream. Extinction by film breakdown appears to be a fundamental difficulty of systems using fixed surfaces to support a liquid film supplied externally and spread by gravity.

In addition to the above qualitative effects, changes in air speed also influenced the rate of combustion from the rod, as shown in fig. 8 for a 1/8in. diameter brass rod, expressed as a unit combustion rate in terms of pounds of fuel burnt per second per inch length of rod.

Spalding employed a non-dimensional combustion rate, S, defined as $S = M C_p/k$, where

$M = (1/\pi)$ x unit combustion rate

C_p = specific heat of air, and

k = thermal conductivity of air.

The relationship between S and Reynolds Number was found to be $S = 0.1615 \ (Re)^{0.493}$ over a range $Re = 1600$ to 11,200, which correlates well with Spalding's value of $0.160 \ (Re)^{0.5}$ over a range $Re = 300$ to 6,000.

The effect of changes in air temperature on the non-dimensional combustion rate was investigated over the limited range of 34°C to 54°C, and the combustion rate was found to increase appreciably with temperature (fig. 9). No direct means of air heating was available, but by allowing the air and fuel temperature to vary together, and then varying the fuel temperature separately, the effect of changes in air temperature alone was found by difference, and was converted to a standard fuel temperature of 70°C.

As a turbulent boundary layer increases the overall heat transfer (ref. 4), tests were made with two thin wires fastened longitudinally to the surface of the rod at $\pm 45°$ and then $\pm 135°$ from the stagnation point. In the first case, the combustion rate was slightly higher, but the air speeds for droplet separation and for extinction were less. In the second case, the extinction speed was about 15 per cent higher, but the combustion rate less.

3.1.2 Influence of Fuel Conditions

For each inlet air velocity, a narrow range of fuel flow existed for the maintenance of a flame stabilised on the entire length of the rod. Within this range, the flame length increased progessively down the length of the rod, to reach a maximum near the bottom of the rod, or just above the point where no fuel remained. The reduced flame length at the top was due to quenching by the cold entering fuel, as the fuel flow over the rod was a maximum at this point. The weak limit of combustion was identified with the flame shrinking towards the top of the rod, burning all the fuel before any could complete its journey down the rod. When the rich limit was reached, the flame shrank to the bottom of the rod due to extensive quenching.

The fuel temperature was varied over the range 35°C to 130°C by means of an electric heater. The effect on non-dimensional combustion rate can be expressed as $S = 4.5 + 0.01712\ t_k$, where t_k = kerosine temperature in °C. Above 110°C, visible yellow flames indicated the onset of fuel cracking.

3.1.3 Influence of Rod Conditions

In addition to the standard rod of 1/8in. diameter, a series of rods of diameters 1/4in. to 1in. was tested. A slightly higher extinction air speed was found for the 1/4in. rod, but this fell with further increase in diameter. As droplet separation occurred earlier and combustion instability was experienced with all rods of diameter greater than 1/8in. this minimum diameter was adopted as standard.

The effects of surface finish were investigated by comparing four rods arranged in increasing order of roughness as polished, normal finish, sand-blasted, and rough filed. The air speed for droplet separation was found to fall with increased roughness, but no appreciable change was noted in combustion rate.

No detailed investigations were made into rod cross-sectional form, but the results of Hilpert and others (Ref. 5) show that no great improvements are obtained from elliptic, square, or hexagonal cross-sections. It would appear advantageous to use a section incorporating fixed vanes to project into the flame region and conduct heat back to the main body of rod. As an approach to this type of rod design, a threaded 1/8in. diameter rod was used. This gave an increase in combustion rate of about 30 per cent, but the droplet separation speed was less than that for the polished rod. No further investigations were made in this direction, and the 1/8in. diameter polished brasz rod was retained as standard.

3.2 Tests with a Single Row of Rods

Tests were carried out with different spacings between rods fitted in a single row at the outlet of the open chamber (fig. 10), the maximum number of rods that could be conveniently fitted in a single row being five, with 0.875in. between centres. This five rod arrangement, which gave a non-dimensional combustion rate slightly higher than that for a single rod due to the proximity of the individual flames, was adopted as the standard single row.

The row was then fitted into the closed chamber (see fig. 3), and tests were carried out over a range of air mass flow from 0.162 to 0.987 lb./sec. (i.e. from about 11 to 66ft/sec. inlet air speed). The extinction speed in the closed chamber was lower than that in the open chamber, due to the loss of the stabilising turbulence created at the open-chamber outlet, and to the increased local air speed in the plane of the rods. Small inlet shield devices were developed (see fig. 7) which masked the rods from the vorticity effects within the boundary layer at the top of the rods, and increased the extinction speed to about 66 ft./sec. Difficulty was experienced in watching and adjusting all the flames at once as the air speed was varied.

As before, a blue open-wake flame could be established along the whole length of each rod only over a narrow range of fuel flow for each value of air speed, and visual observation was essential during flame adjustment. The optimum fuel flows for full-length flames over the five rods were found to range from 4.79×10^{-4} to 11.40×10^{-4}lb./sec., giving values of overall air/fuel ratio ranging from 334/1 at low air speeds to 865/1 at extinction. The non-dimensional combustion rate dropped to $0.135(\text{Re})^{0.5}$, i.e. below that for a single rod in the open chamber. Typical performance curves for the single-row system are given in fig. 11.

A hard gritty deposit of carbon was found to build up on the downstream surfaces of the rods, probably due to fuel cracking on the rod surface and to re-circulation by wake eddies of incompletely burnt particles. Sufficient deposit accumulated in about four hours running to cause distortion of the flame.

The quantities of unconsumed fuel returned to the drain manifold ranged from 48 per cent at low air speed to nil at extinction. Due to the re-circulating nature of the fuel system used with this type of burner, preferential burning of the fuel supplied to the rods was unavoidable, and the fuel in the main tank steadily grew richer in the higher boiling components. A.S.T.M. distillation tests carried out on fuel samples taken after a four hour run indicated a measurable loss of light and medium boiling fractions over the original fuel (fig. 12). Gravity feeding, and the above progressive reduction in fuel volatility, are inherent drawbacks to such a fuel system, and might both be avoided by the use of porous rods supplied internally with fuel under pressure. (See section 3.4). The individual characteristics of the five-rod single-row arrangement are discussed further below.

3.2.1 Temperature Variation

The outlet traverse section was first located at a distance of 17.5in. (140 rod diameters) downstream from the burner grid, and a vertical traverse at 0.5in. intervals at the chamber mid width, together with a horizontal traverse at 0.2in. intervals at the chamber mid height, gave the results shown in figs. 13 and 14. These temperature profiles became more uniform at higher air speeds, the vertical profiles corresponding closely with the flame contours.

The percentage temperature variation across the outlet plane was defined by

$$\frac{(\text{maximum temperature} - \text{mean temperature})^{\circ}\text{C}}{\text{mean temperature}^{\circ}\text{C.}} \times 100,$$

the mean temperature being obtained from measurements made in 45 positions in the outlet plane, at 0.5in. horizontal intervals and 1.2in. vertical intervals. The traverses were then repeated at distances of 12in. and 8in. from the burner grid, and the results given in fig. 15 show the variations to be about 40 per cent for all distances at the higher air speeds, and to be excessive for the shorter distances at the low air speeds.

3.2.2 Combustion Intensity

The maximum combustion intensity recorded with the 17.5in. chamber length was 0.107×10^6 C.H.U./hr. ft.^{3} atmosphere, which occurred at the maximum air mass flow of 0.987 lb./sec. This value represented a combustion temperature rise of about 40°C, with a temperature variation above the mean of 26°C (+ 31 per cent). Based on the 8in. chamber length, this intensity rises to 0.234×10^6 C.H.U./hr.ft^3 atmosphere. The minimum chamber length possible is that equal to the length of the flame (approximately 3in.), which gives a further increase of the intensity to 0.624×10^6 C.H.U./hr.ft.^{3} atmosphere.

3.2.3 Combustion Efficiency

The combustion efficiency, defined as the ratio of the actual to the theoretical rise in total temperature through the chamber, was determined over the standard range of air speed. The actual temperature rise was found by direct measurement at the inlet and outlet planes, and the theoretical temperature rise by use of the enthalpy chart in fig. 16. Although some calculations at low air speeds yielded combustion efficiency values greater than 100 per cent, the present method using 45 traverse positions was considered to be sufficiently accurate to reveal changes in combustion efficiency, as plotted in fig. 17.

3.2.4 Pressure Loss

The loss in total pressure through the combustion chamber was measured for the chamber alone (i.e. loss due to wall friction), for the single row without fuel, and for the single row with combustion taking place. The mean outlet dynamic head was measured by means of a traverse at 45 positions, and the loss in pressure was defined as.-

$$\text{Pressure Loss Factor} = \frac{\text{Loss in Total Head}}{\frac{1}{2}\rho_i v_i^2}$$

where ρ_i and v_i are the inlet density and velocity respectively. The two 'cold' loss factors are plotted in fig. 18. The pressure loss factor due to combustion has been shown, as in ref. 6, to be approximately directly proportional to

$\frac{T_{ot} - T_{it}}{T_{it}}$, where T_{it} and T_{ot} are the inlet and outlet total temperatures respectively, for low values of Mach number in the chamber. The total pressure loss factor may therefore be expressed as.-

$$\text{Total Pressure Loss Factor} = K_1 + K_2 \left(T_{ot}/T_{it}\right).$$

Fig. 19 shows a reasonably straight line relationship between the total pressure loss factor and the temperature ratio.

3.3 Test with a Double Row of Rods

Preliminary tests were made in the open chamber using a second row of five rods 5in. downstream of the first row, with the rods arranged in line. Violent boiling and cracking occurred of the fuel on the downstream rods, and the rods themselves twisted and melted under the heat. A staggered arrangement was then tested, with four rods in the first row and five in the second, at a row spacing of 3in. The appearance of the flames on the second row was not good due to the instability caused by the loss in air momentum at such a distance from the open end of the chamber.

Double row tests were then carried out in the closed chamber where improved combustion was found, although overheating of the downstream rods occurred when the rods were starved of fuel. Temperature traverses were made at the standard 17.5in. distance from the first row, for the double in-line rows of five rods at 5in. spacing, and for a staggered arrangement at 3in. spacing with five rods in the first row and four in the second. Values of temperature variation and combustion efficiency were determined and are included in figs. 15 and 17 respectively. In general, both droplet separation and extinction speeds were lower than those for the standard single row.

3.4 Tests with a Porous Rod

As indicated in section 3.2, the gravity feed and volatility change problems might be solved by using hollow porous rods blanked at one end and fed internally with fuel under pressure. With uniform porosity of the tube material, individual rod flow controls could be eliminated.

Hollow rods of sintered stainless steel were made available by B.S.A. Ltd. in 3/8in. O/D, and in 4in. lengths. A 6in. length was made up by butt joining with plastic metal, and was mounted centrally in the closed chamber, Fuel was supplied under the standard pressure head of 3 ft. For comparative purposes, a rod of 'solid' mild steel was also tested under the same conditions. Combustion was established satisfactorily from the porous rod but, due to the increased surface roughness, the extinction speed was reached at 45 ft./sec., as compared with 65 ft./sec. for the mild steel rod. The carbon deposit built up rapidly by lodging in the pores (fig. 20), and the fuel flow at constant head dropped progressively to half its original value after a continuous run of ten hours. Blockage due to fuel-borne material was avoided by filtering the fuel through a similar porous rod before entering the combustion chamber.

In order to investigate the surface temperature conditions controlling the rate of carbon build-up, a chromel-alumel thermocouple was passed into the surface of the mild steel rod through a small drilled hole. The rod was rotated through 180° whilst combustion was taking place from it, and the test was repeated with and without combustion from the rod when a second rod, with combustion, was located 5in. upstream. Typical results are shown in fig. 21, but comparative tests with a porous rod could not be carried out due to rod supply difficulties.

4. Comparison with Derwent I. Combustion Chamber

To complete the practical assessment of the cylindrical rod burner system, comparative performance results were taken from tests carried out on a Derwent I. combustion chamber operating at similar inlet conditions. The operating conditions and performance characteristics of both the Derwent chamber and the standard single-row five-rod grid are shown below.-

Combustion Chamber	Derwent I.	Single-row 5-rod grid 17.5in. chamber length
Air inlet temperature, °C	18	40
Air inlet pressure, atmos.	1.04	1.02
Air inlet velocity ft/sec.	137	53 *
Air velocity, based on max. cross-sectional area, ft/sec.	42	
Air mass flow, lb/sec.	1.17	0.79
Air/fuel ratio	73/1	779/1
Temperature rise, °C	500	45
Combustion intensity, C.H.U./hr.ft.^{3} atmos.x 10^6	1.20	0.099
Combustion efficiency %	92	88
Temperature variation %	33	33

* The air velocity of 53 ft./sec. is not the maximum attainable, but is a compromise to give almost maximum combustion intensity at a reasonable combustion efficiency. (See Fig. 11)

In order to provide a common basis for comparison, a grid burner chamber was envisaged to produce, theoretically, an intensity closer to that of the Derwent chamber, at an equivalent air/fuel ratio. It is suggested by Spalding (ref. 7) that combustion intensity should be based on the flame length rather than an arbitrary chamber length. The flame length has therefore been taken as 3in. in the following calculations and the number of rods in the row increased to 9 to give a combustion intensity of 1.01 x 10^6 C.H.U./hr.ft.^{3} atmos., which is of the same order as that in the Derwent chamber. Increasing the number of rods reduces the air/fuel ratio to 432/1, and increases the temperature rise to 72°C.

Adding further rows of rods at a row spacing equal to the flame length, with the total chamber length extending from the upstream row to the end of the downstream flame, will not increase the combustion intensity, but will reduce the level of air/fuel ratio towards that used in current practice, as shown.-

Combustion Intensity	Constant at 1.01 x 10^6 C.H.U./hr.ft.^{3}atmos.					
No. of 9-rod rows	1	2	3	4	5	6
Chamber length, in.	3	6	9	12	15	18
Overall air/fuel ratio	432	212	144	108	87	72

It follows that a six-row arrangement would be necessary to give values of air/fuel ratio equivalent to that in the Derwent chamber. The length of the grid burner chamber is a little less than that of the 25in. long Derwent chamber, but the 18in. length quoted does not include the diffuser length necessary to reduce the air speed from the compressor outlet. The overheating difficulties experienced with the downstream row of a two-row arrangement are likely to be greatly magnified when further rows of rods are introduced into the chamber.

5. Discussion and Conclusions

Combustion systems constructed of a multiplicity of small elements appear attractive from the aspects of low pressure loss and short chamber length, and would permit full-scale development from small-scale test results. Tests with a single cylindrical element show a narrow critical range of fuel flow at each air flow for the establishment of a satisfactory full-length flame, together with low values of air speed for droplet separation and flame extinction. A tendency exists for the formation of carbon on the downstream surface of the element.

Performance characteristics of a single row of rod elements show a poor temperature distribution at short distances behind the flames. The combustion intensity is reasonable in value but is localised, with a very high air/fuel ratio. The combustion efficiency falls sharply as the maximum air speed is approached. The pressure drop is exceptionally low (pressure loss factor for a single row of 9 rods = 2.0, compared with current value of 30), which would permit the use of turbulent promoters to improve the temperature distribution.

Multi-row chambers can be envisaged to give values of combustion intensity and air/fuel ratio comparable with those from a conventional chamber working under similar, adverse, inlet conditions. The total pressure drop would be lower than current values, and the temperature distribution should be reasonable. However, experimental evidence to date suggests overheating difficulties of the downstream rods, with extra-long flames, cracking of the fuel, and very poor combustion efficiency. The critical nature of the air and fuel flow relationship infers a narrow stability loop in practice. Further, the total chamber length is probably no less than that of conventional chambers.

Extensive investigations were not made into the beneficial effects of increased inlet air pressure and temperature, but the general inference is that a cylindrical rod can only be looked upon as a preliminary elemental device. Other sectional shapes, together with shields and turbulence promoters, may improve the overall performance. The most promising line of investigation appears to be the development of porous burner elements of non-circular section, fed internally with fuel under pressure. The section may include fins to direct the flame heat back to the element, or may be in the form of a stalled blade burning fuel from the convex surface. In this connection, only parts of the section need be porous, to constrain the flow of fuel to the required surfaces for combustion. Temperature measurements show that downstream elements may be subjected to surface temperatures of about 350°C, and correspondingly higher temperatures if more than two rows are used. Fine filtration of fuel is essential with the use of porous rods, and difficulties may be experienced due to the formation and adhesion of carbon.

The following general conclusions may be drawn.-

(i) Cylindrical rod elements, of 1/8in. diameter, only permit satisfactory combustion of surface fuel over a narrow air/fuel ratio range, difficult to select without the assistance of visual observation.

(ii) These elements lose fuel droplets by separation at low air speed, of approximately 40 ft./sec., and are at present unable to support combustion at a speed in excess of about 70 ft./sec.

(iii) A tendency exists for the formation of carbon on the downstream surface of the elements.

(iv) The temperature distribution is poor in planes close to a single row grid.

(v) When fitted in a multi-row arrangement, a tendency exists for over-heating of the downstream rods, leading to fuel boiling and cracking, long flames, poor combustion efficiency, and thermal damage to the elements.

(vi) The elemental burner grid system has the advantage of very low pressure loss, which permits the inclusion of shields to increase the extinction speed, and of turbulence promoters to improve the temperature distribution, when suitable devices have been developed.

(vii) The performance of hypothetical burner grid system constructed of cylindrical rods could only be made to approach that of a conventional spray-type chamber by making a number of assumptions, some of which are not substantiated by the experimental experience gained. The stability loop of the grid chamber is likely to be narrow, and the overall chamber length no shorter than that of the conventional chamber.

(viii) Cylindrical rods are not satisfactory as elemental burners for a high performance combustion chamber, but further development may be worthwhile of porous burner elements of non-circular section, fed internally with fuel under pressure. Difficulties may be experienced due to blockage by fuel-borne solids, and by the formation of carbon on the downstream surface of the elements.

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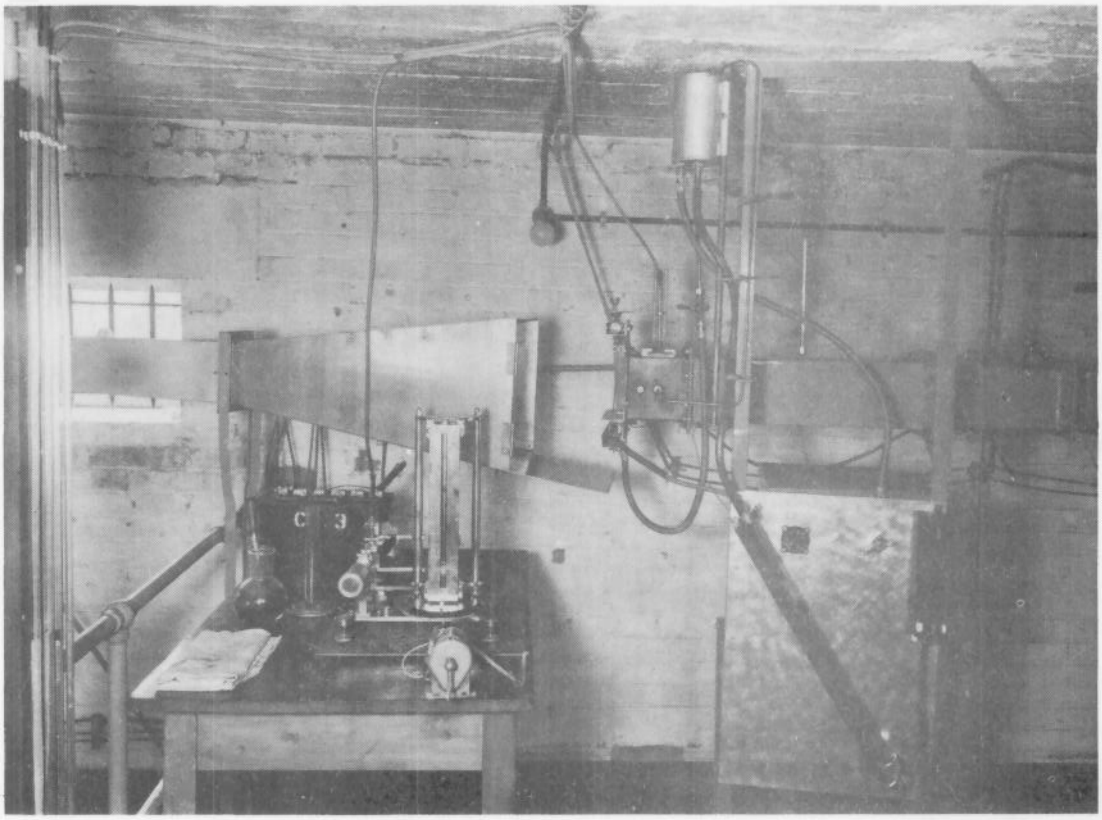
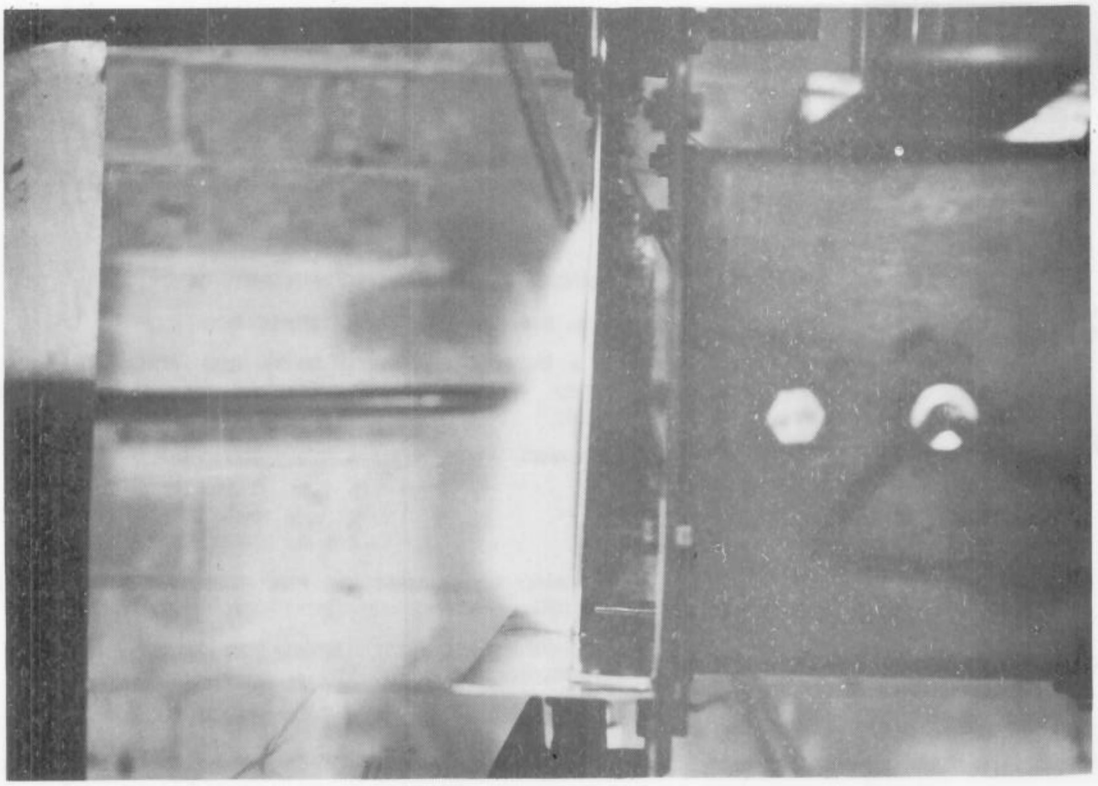
FIGS. 1 & 2.



OPEN COMBUSTION CHAMBER AND ASSOCIATED EQUIPMENT.

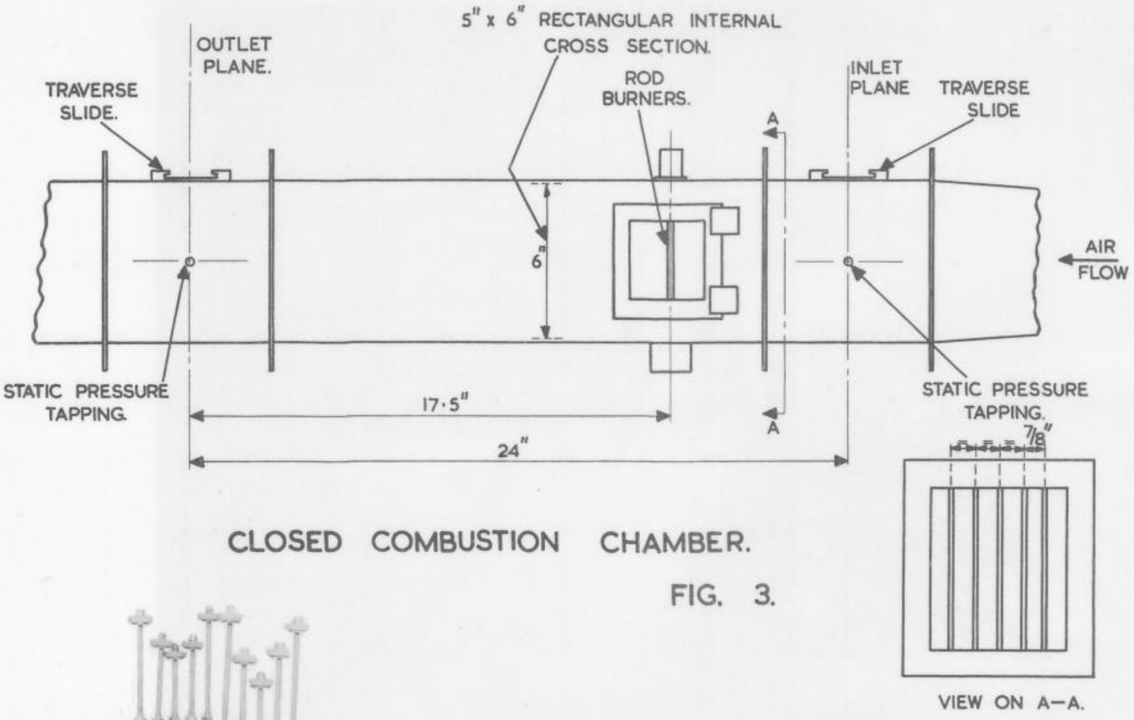
FIG. 1.



COMBUSTION FROM A SINGLE ROD IN THE OPEN CHAMBER.

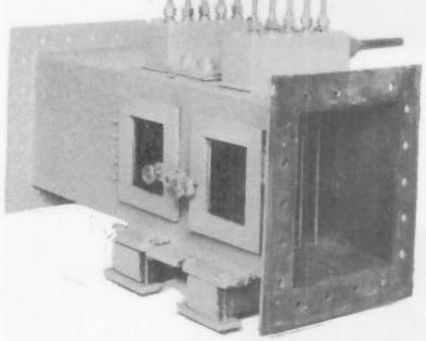
FIG. 2.

FIGS. 3, 4 & 5.



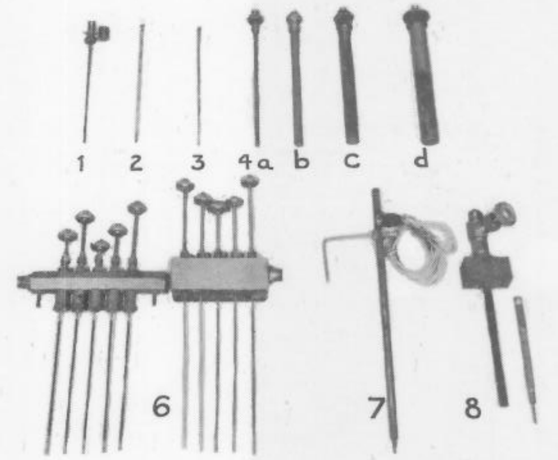
CLOSED COMBUSTION CHAMBER.

FIG. 3.



CLOSED COMBUSTION CHAMBER FITTED WITH TWO ROWS OF RODS.

FIG. 4.

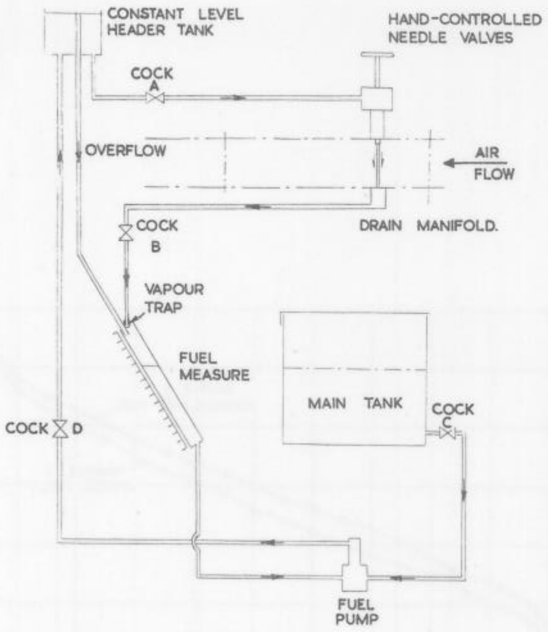


TYPES OF BURNER ROD AND GRID.

FIG. 5.

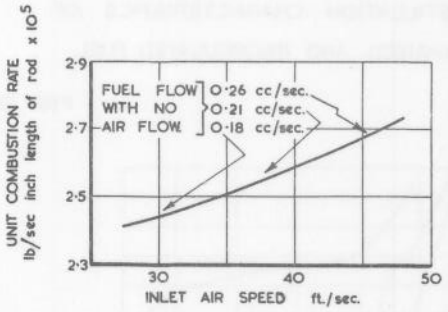
KEY:—

1. STANDARD 1/8 in. DIAMETER POLISHED BRASS ROD.
2. 1/8 in. DIAMETER THREADED BRASS ROD.
3. 1/8 in. DIAMETER POLISHED BRASS ROD WITH TWO FINE WIRES ATTACHED AT 45° FROM THE FORWARD STAGNATION POINT.
4. POLISHED BRASS ROD.
   - a. 1/4 in. DIAMETER.
   - b. 1/2 in. DIAMETER.
   - c. 3/4 in. DIAMETER.
   - d. 1 in DIAMETER.
6. STANDARD SINGLE ROWS OF FIVE RODS SPACED AT 0.875 in. CENTRES, SHOWING ALTERNATIVE FEED MANIFOLDS.
7. HOLLOW 3/8 in. DIAMETER STEEL ROD FITTED WITH WALL THERMOCOUPLE.
8. POROUS 3/8 in. DIAMETER STAINLESS—STEEL RODS.



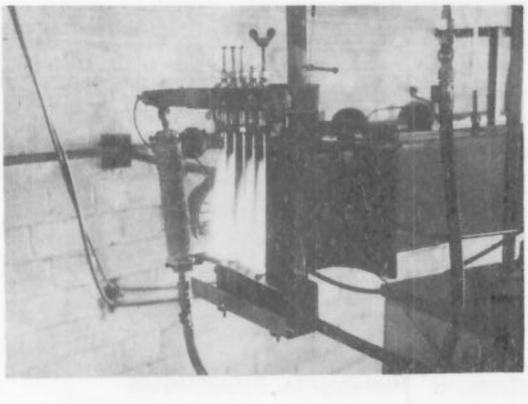
FUEL SYSTEM

FIG. 6.



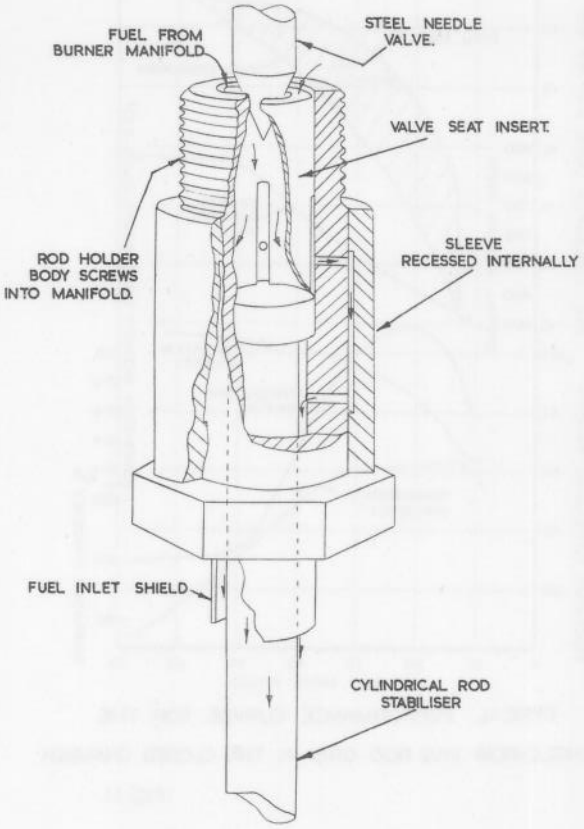
TYPICAL VARIATION IN UNIT COMBUSTION RATE WITH AIR SPEED.

FIG. 8.



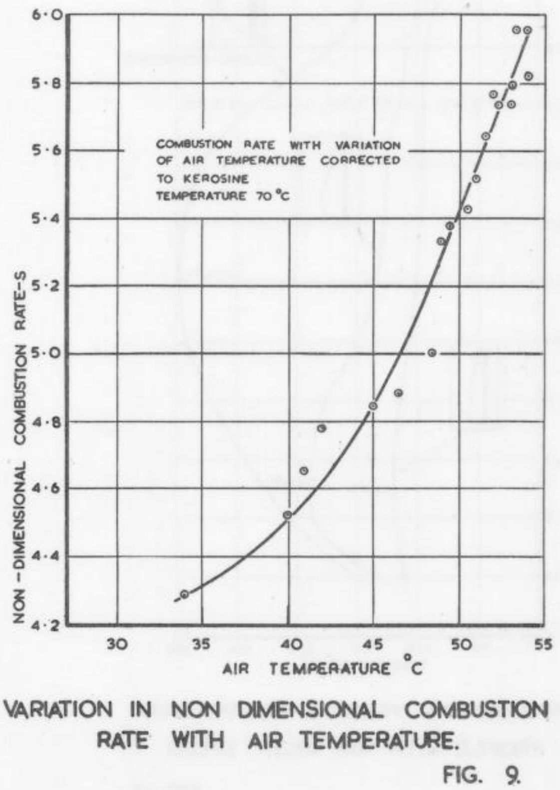
COMBUSTION FROM SINGLE ROW OF FIVE RODS IN THE OPEN CHAMBER.

FIG. 10.



ROD FUEL CONTROL

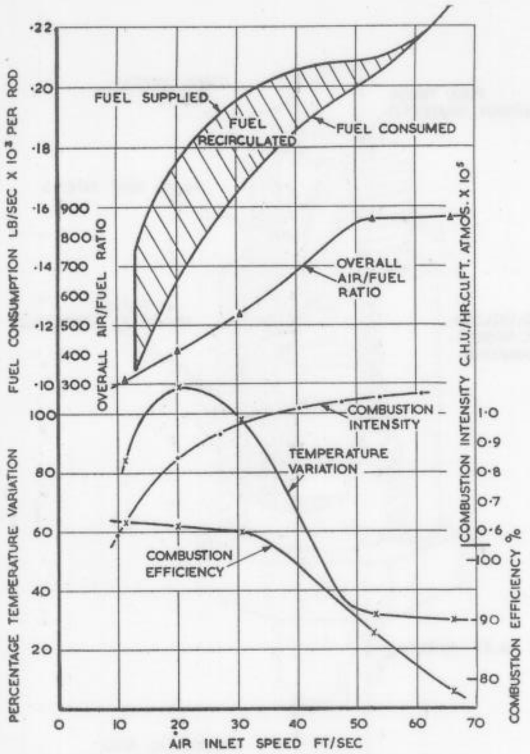
FIG. 7



VARIATION IN NON DIMENSIONAL COMBUSTION RATE WITH AIR TEMPERATURE.

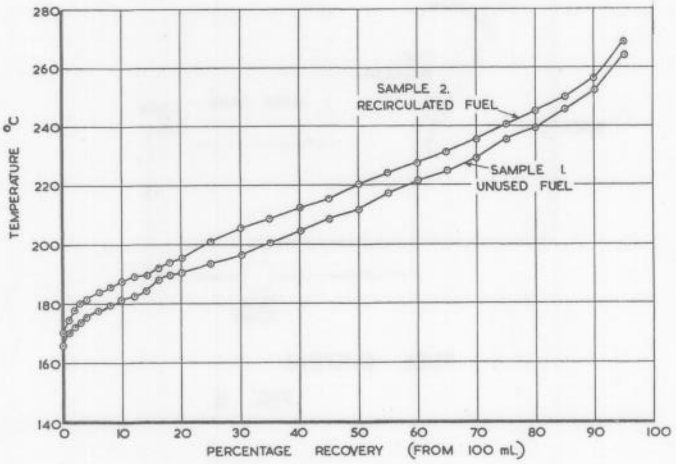
FIG. 9.

FIGS 11. 12. 13. & 14.



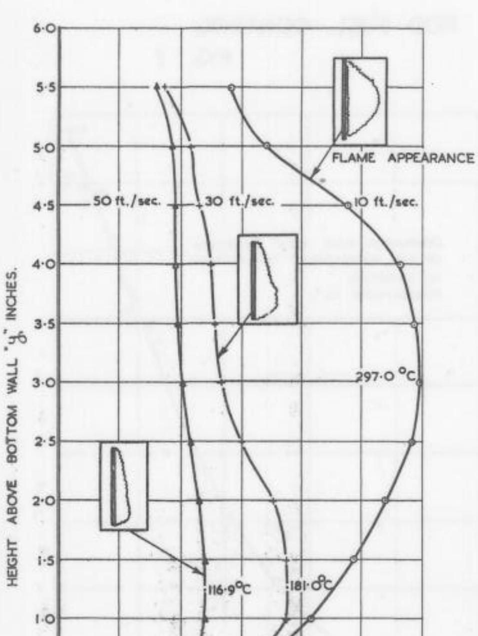
TYPICAL PERFORMANCE CURVES FOR THE SINGLE-ROW FIVE ROD GRID IN THE CLOSED CHAMBER

FIG. 11.



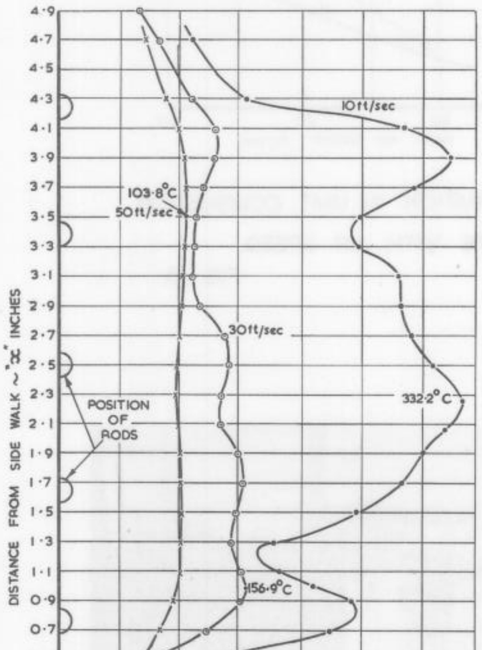
DISTILLATION CHARACTERISTICS OF UNUSED AND RECIRCULATED FUEL

FIG. 12.



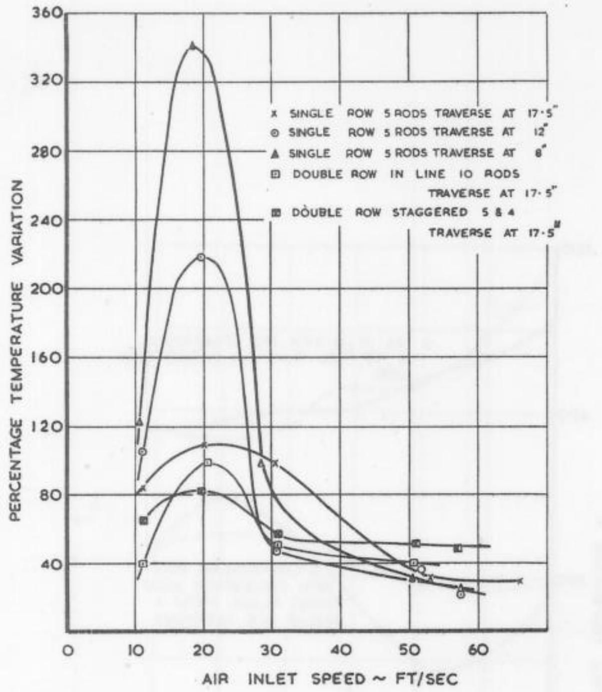
VARIATION IN VERTICAL TEMPERATURE PROFILE WITH AIR INLET SPEED

FIG. 13.



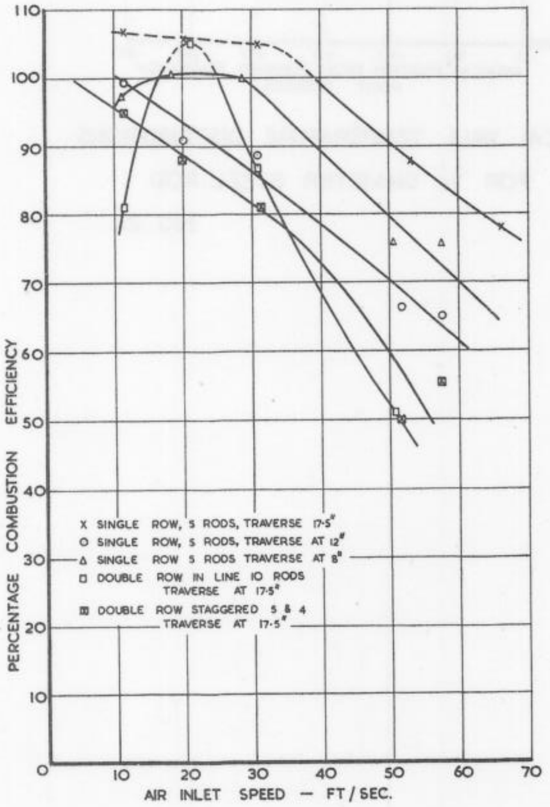
VARIATION IN TRANSVERSE TEMPERATURE PROFILE WITH AIR INLET SPEED

FIG. 14.



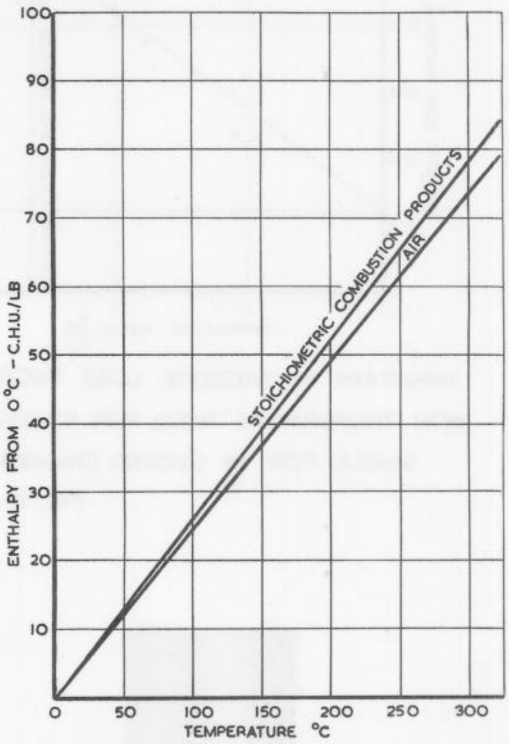
TEMPERATURE VARIATION VERSUS AIR INLET SPEED.

FIG. 15.



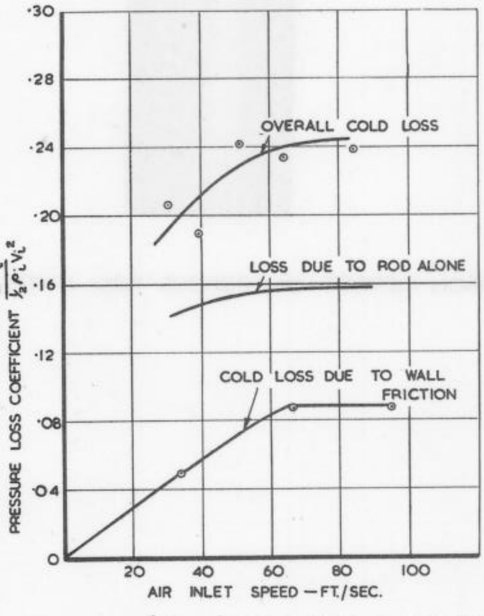
VARIATION IN COMBUSTION EFFICIENCY WITH AIR INLET SPEED.

FIG. 17.



ENTHALPY OF AIR AND OF THE STOICHIOMETRIC COMBUSTION PRODUCTS OF AVIATION KEROSINE.

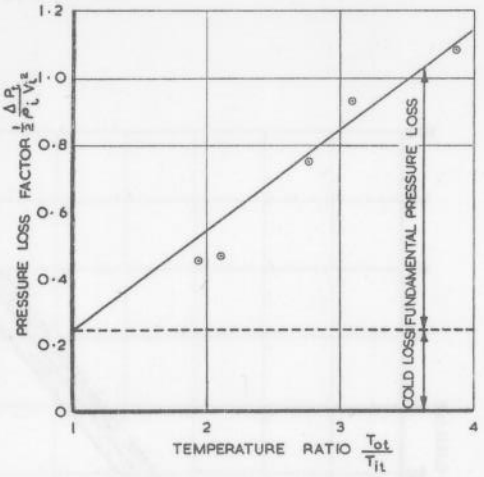
FIG. 16.



VARIATION IN 'COLD' PRESSURE LOSS WITH AIR INLET SPEED FOR STANDARD SINGLE ROW IN CLOSED CHAMBER

FIG. 18.

FIGS 19. 20. 21.

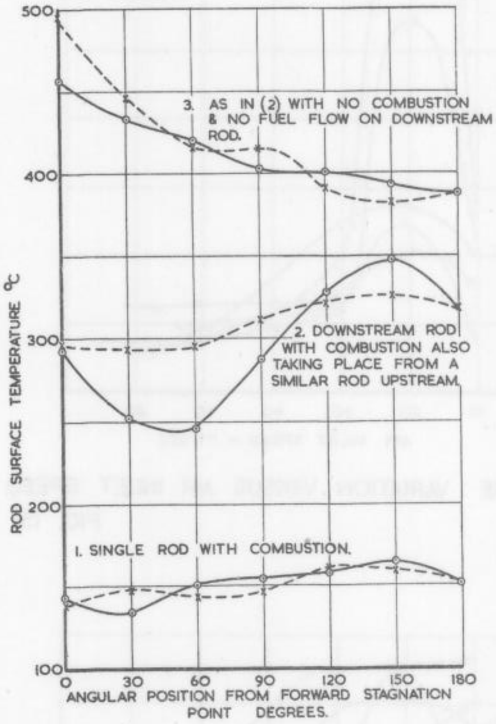


VARIATION IN PRESSURE LOSS FACTOR WITH TEMPERATURE RATIO, FOR STANDARD SINGLE ROW IN CLOSED CHAMBER

FIG. 19.

CARBON DEPOSIT ON POROUS ROD AFTER 10 HR. RUN

FIG. 20.



TYPICAL WALL TEMPERATURE DISTRIBUTIONS FOR $^3/_8$" DIAMETER STEEL ROD

FIG. 21.