ON PERFORMANCE CHARACTERISTICS OF COMBUSTION CHAMBERS WITH GRADUAL ADMISSION OF OXYDIZER ALONG THE CHAMBER

By V. E. Doroshenko

Academy of Sciences, U.S.S.R.

INTRODUCTION

Combustion chambers with gradual admission of one of the two components along the chamber are widely used in practice. Recently, suppositions have been put forward that performance of such arrangements greatly depends on chemical reaction rate, though the reaction occurs as the mixing of the components takes place. It should be noted that the experimental confirmation of these suppositions and the theory of the process taking place in such arrangements are lacking. For example, there was no explanation of the nature of the combustion efficiency dependence on the air parameters, equivalence ratio and distribution of air admission along the flame tube of an aviation gas turbine combustion chamber.

In the present paper a theoretical analysis of the combustion process in an aviation gas turbine combustion chamber is given (in qualitative manner), under the assumption about the decisive role of the chemical reaction rate. Comparison of theoretical results with experimental data shows that such assumption is valid.

COMBUSTION PROCESS MODEL

Consider an idealized combustion chamber model shown in Fig. 1. Suppose that the flow of gases is one-dimensional and neglect the variation of pressure P_c along the chamber and heat losses to the surroundings. The air flow entering the combustion chamber is divided into two parts. Denote the air mass flow rate through the primary zone by M_{a1}, the fuel mass flow rate by M_f, the mass flow rate of air supplied to the secondary zone by M_{a2}.

To ensure stable burning over the wide range of the operational conditions one seeks to keep the mean gas velocity as low as possible in that part of the flame tube where the re-circulation zone is placed.

It is achieved by supplying a comparatively small part of the total air flow into the primary zone. Because of small gas velocity the residence time of the gases in the primary zone is sufficiently long, consequently the mixture prepared during the mixing process has time to react in accordance with air contents. As a result the fuel burning rate is not limited
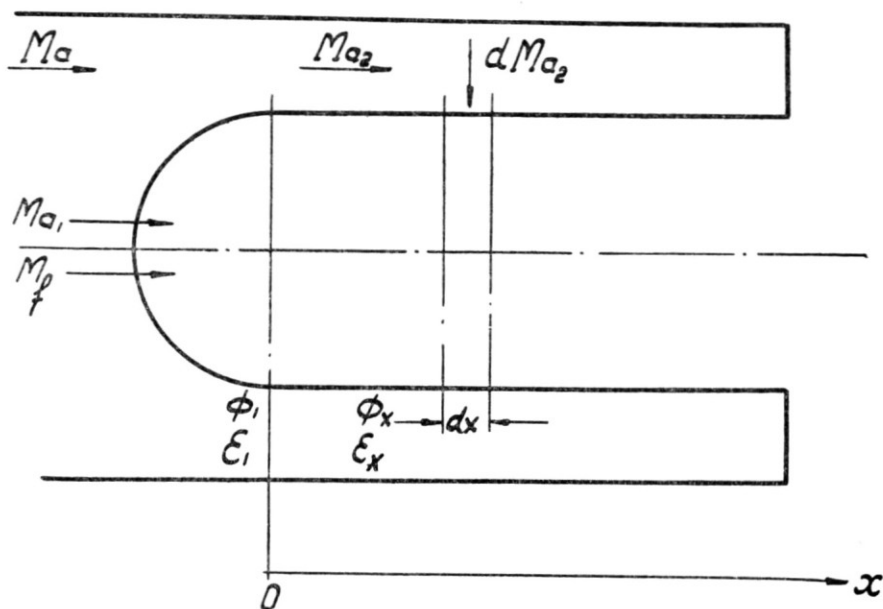

FIG. 1. Scheme of the combustion chamber.

by the reaction rate. However only a small part of the fuel can be burned in the primary zone for the lack of air here. Numerous experimental data show that combustion efficiency at the primary zone exit ε_1 weakly depends on the air parameters at the chamber inlet (because of the long residence time of gases in the primary zone); its value is determined mainly by the equivalence ratio at the primary zone exit (Φ being more than unity), as well as by the mixing. Let us denote the effect of mixing by β, so $\varepsilon_1 = \beta \dfrac{1}{\Phi_1}$. Generally, with the help of β one may characterize the effect of air parameters when necessary (i.e. in flight at very high altitudes, in altitude relighting).

Denote combustion efficiency at the section x by ε_x, equivalence ratio by Φ_x. Suppose that the secondary air is delivered continuously along the flame tube and is rapidly mixed with the gases inside the flame tube in each given cross-section. Existence of intense mixing inside the flame tube has been established in[1]; the measurement results have shown that

turbulence intensity exceeds 50 per cent (i.e. fluctuation velocity exceeds half of the local mean velocity). Suppose also that there are neither mixing nor heat transfer along the flame tube; neglect the kinetic energy of the gases. The purpose of the procedure is to determine the variation of the combustion efficiency along the secondary zone ε_x and the value of overall combustion efficiency at the combustion chamber exit ε as a function of the physical, chemical and design parameters.

To determine the variation of the burning process along the secondary zone under the assumptions mentioned above we shall use the equation which describes sufficiently well (as numerous experimental data show) the effective combustion reaction of hydrocarbons.

$$w = C_f^m C_a^n Be^{-\frac{E}{RT}}$$

According to the experimental data $m+n = 1\cdot3-1\cdot8$ for hydrocarbon mixtures[2]. The calculation can give only qualitative results because of the simplifications made above and because the order of the reactions in the combustion chamber is unknown; for these reasons it is supposed that the burning takes place through the bimolecular reaction, so that $m = n = 1$.

Replacing C_f, C_a, w by suitable values, the equation was derived for the dependence of ε_x on dimensionless distance along the secondary zone X

$$\frac{d\varepsilon_x}{dX} = ak_\phi \frac{D^3 P_c T_c}{V_c} \frac{(1-\varepsilon_x)\left\{\frac{1}{\phi}[b+\varphi(X)(1-b)]-\varepsilon_x\right\}}{T^2[b+\varphi(X)(1-b)]^2} e^{-\frac{E}{RT}} \qquad (1)$$

where $X = x/L$ (L–length of the secondary zone), a is constant value (for a given fuel), $k = L/D$ (D–flame tube diameter), V_c, P_c, T_c, are correspondingly volume rate, pressure and temperature of the air, T is temperature of gases along the secondary zone, Φ is overall equivalence ratio, $\varphi(X)$ is the function which determines the air distribution along the flame tube, $b = M_{a1}/M$ a is the relative part of the primary air flow.

EFFECT OF AIR PARAMETERS

Figure 2 shows the relationship between combustion efficiency ε_x and the dimensionless distance along the secondary zone X for different values of the volumetric flow V_c. For this case it was supposed that ε_1 is constant and equals $\beta\frac{1}{\phi_1} = \beta\frac{1}{\phi} b = 0\cdot8 \frac{1}{0\cdot5} 0\cdot25 = 0\cdot4$. Two circumstances should attract our attention: (1) combustion efficiency ceases to increase when X approaches a certain value; (2) the greater the value V_c the nearer to the exit section of the primary zone the increase ε_x is stopped. This indi-

cates that the deterioration of the conditions for burning takes place ("chilling" of the reactants): heat release rate during reaction process becomes insufficient to raise the temperature of the incoming air and the gas to the value of the temperature at which intense chemical reaction
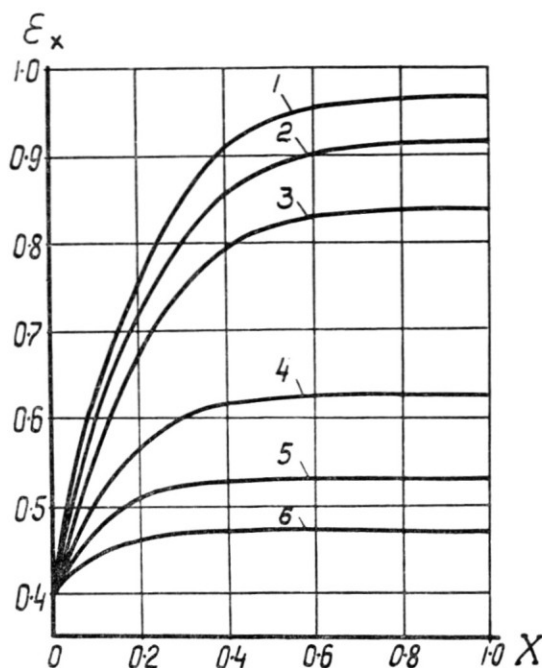

FIG. 2. Combustion efficiency along the secondary zone.
$b = 0.25$; $P_c = 1.5$ atm; $T_c = 300°C$; $\Phi = 0.5$.

	1	2	3	4	5	6
V_c, m³/sec	0.5	0.75	1.0	1.5	2	3

occurs. Obviously if the burning ceases in some section of the flame tube the part of the flame tube length behind this section becomes useless (for increasing ε). The situation can be improved in some degree by changing the distribution of secondary air (see below). This result has been confirmed experimentally.

From equation (1) and Fig. 2 it is seen that overall combustion efficiency falls when V_c rises. The same phenomenon occurs in real combustion chambers, and it is possible to restore the high value of the overall combustion efficiency of ε by increasing the air temperature.

Since the atomization and evaporation of fuel, the mixing process and chemical reactions take place simultaneously, a question arises: which

of these processes determines such a character of the relationships be-
tween ε and V_c, T_c. For elucidation of this question a comparative test
was made by injecting liquid and vapor fuels into the same combustion
chamber.

Curves $\varepsilon = f(V_c)$ for several values of the air temperature are presented
in Fig. 3. Analysis shows that: (1) in the case of injecting the vapour fuel
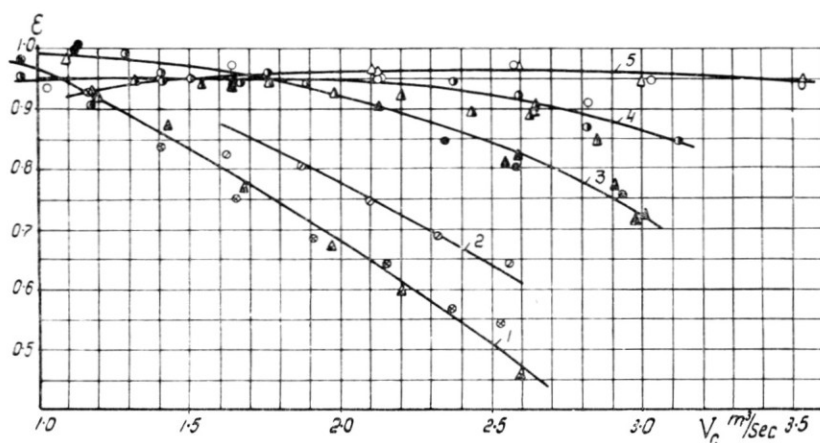ε falls steeply with increasing of V_c if the air temperature is compara-

FIG. 3. Dependence of combustion efficiency ε for liquid and vapourized fuels
on air volumetric rate for various air temperatures.
$$P_c = 1 \cdot 4 - 1 \cdot 7 \text{ atm}; \quad \Phi = 0 \cdot 167.$$

	1	2	3	4	5
t_1, °C	14	40	100	200	300

— ▲ — △ — liquid kerosene
⊕ ⦺ ◕ ◑ ○ — vapourized gasoline

tively low, (2) curves corresponding to burning of both liquid and vapour
fuels practically coincide; this means that if the pressure of the liquid
fuel at a nozzle is sufficient for good atomization, the vaporization
process of droplets finishes so rapidly that it does not limit the burning
even when V_c increases considerably, (3) increasing of the air temperature
results in considerable rise of the overall combustion efficiency ε, not
only of the liquid but also of the preliminary vaporized fuel. These
results show that the chemical reaction is a limiting process responsible
for the fall of the combustion efficiency with the increase of V_c and the
decrease of T_c. The same phenomenon occurs under various air pres-
sures*.

---

* Under very low air pressures (below 260–250 mm Hg) the deterioration of the
mixing process influences the combustion process as well.

Thus, these experiments prove the validity of the supposition about a considerable role of the kinetic factors in the process taking place in the aviation gas turbine combustion chamber.

EFFECT OF THE EQUIVALENCE RATIO

As was mentioned, the explanation of the nature of the relationship between ε and ϕ (see, for example, Fig. 4) the peculiarity of which is the existence an optimal value of ϕ was lacking. Consider this question using
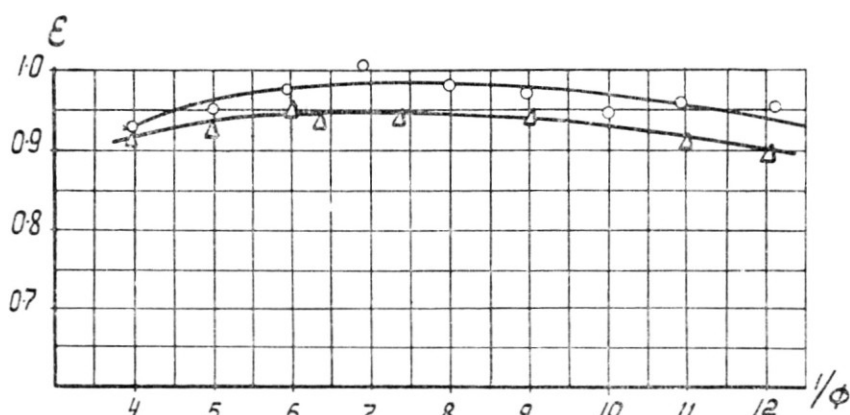

Fig. 4. Dependence of combustion efficiency ε for liquid and vapourized fuels on $1/\Phi$.

$P_c = 1\cdot4$ atm; $t_c = 2\text{C}0°\text{C}$; $V_c = 2\cdot12$ m³/sec.

$\triangle$ — liquid kerosene
$\bigcirc$ — vapourized gasoline.

the conceptions developed above. Figure 5 shows the corresponding data. As in the preceding section it is assumed that $\varepsilon_i = \beta\,1/\phi_1 = \beta b\,1/\phi$, where $\beta = 0\cdot8$, $b = {}^1/_4$. Therefore $\varepsilon_1 = 0$ when $1/\phi = 0$, and $\varepsilon_1 = 1$ when $1/\phi = 5$ (or when $1/\phi_1 = 1\cdot25$). Consequently from $1/\phi = 0$ till $1/\phi = 5$ (i.e. when the mixture becomes leaner) ε_1 rises, when $1/\phi > 0$ $\varepsilon_1 = \varepsilon = 1$. Relationship between ε_1 and $1/\phi$ is shown by the line OBC. In Fig. 5 the maximum possible values of ε are also marked. When $1/\phi > 1$, ε can be equal to unity, when $1/\phi < 1$, ε can in a better case be equal to $1/\phi$. There-

fore the curve $\varepsilon = f(1/\phi)$ is inside the OAB region and on the BC segment.

It is seen that when combustion efficiency in the primary zone ε_1 rises monotonously with the rise of $1/\phi$ till 5, ε at first rises, then falls and again rises up to the value equal to unity. The same phenomenon occurs
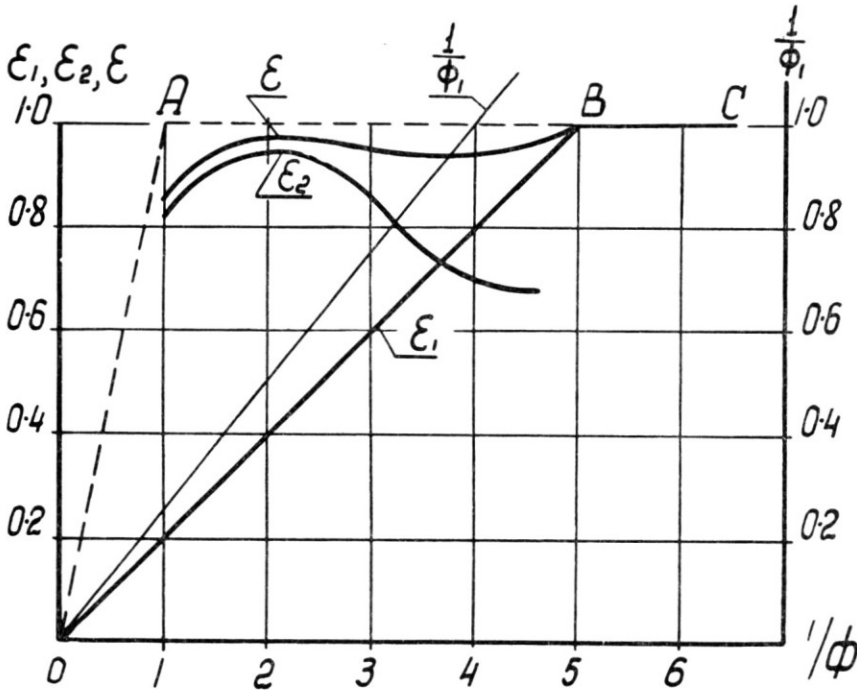

FIG. 5. Dependence of ε_1, ε_2, ε, $1/\Phi_1$ on $1/\Phi$.
$b = 0 \cdot 25$; $\beta = 0 \cdot 8$; $P_c = 1 \cdot 5$ atm; $V_c = 1 \cdot 0$ m³/sec; $T_c = 400°$K.

in real combustion chambers (Fig. 4). The reason is as follows: while $1/\phi$ changes, the efficiency varies not only in the primary zone but in the secondary zone as well. Figure 5 shows the relationship between combustion efficiency in secondary zone ε_2 and $1/\phi$. The values of ε_2 were determined in the following way. Obviously ε_2 is the ratio of the amount of fuel burned in the secondary zone to the amount of fuel supplied to this zone. The latter amount equal $M_f \psi_1$, where M_f is the overall fuel mass flow rate, ψ_1 is the unefficiency in primary zone, which equals

$1-\varepsilon_1$. The amount of fuel burned in the secondary zone is $M_f(\varepsilon-\varepsilon_1)$, consequently

$$\varepsilon_2 = \frac{\varepsilon-\varepsilon_1}{1-\varepsilon_1} .$$

From the analysis of the curve $\varepsilon_2 = f(1/\phi)$ it follows that while $1/\phi$ rises, ε_2 rises, then falls though ε_1 increases (correspondingly the temperature of gases leaving the primary zone the rises). It is explained by the joint influence of both concentration and temperature on the reaction rate: the increase of ε_2 till maximum value is the result of the dominating action of temperature T_1, the decrease of ε_2 after this maximum value is caused by the influence of the concentration of the fuel leaving the primary zone.

Thus the nature of the relationship $\varepsilon = f(1/\phi)$ is determined by the dependence of both of ε_1 and ε_2 on $1/\phi$: firstly while $1/\phi$ increases ε rises because of the increasing of both ε_1 and ε_2, but then ε falls because of the decreasing of ε_2. Further growing of ε is explained by burning of almost all the fuel (and when $1/\phi = 5$, all the fuel) in the primary zone. Such second growth of ε when leaning the mixture occurs in real chambers provided there is no considerable deterioration of atomization.

EFFECT OF SECONDARY AIR DISTRIBUTION

From the development experience on combustion chambers it is known that one can vary the value of ϕ_{opt} by variation of the secondary air distribution along the flame tube (ϕ_{opt} is the value of ϕ at which ε reaches maximum value). However the possible reason of this action was not considered. Discussing this question using equation (1); the air distribution is given by function $\varphi(X)$. Figures 6 and 7 show the curves $\varepsilon = f(X)$ for three cases of the air distribution:

(1) $\varphi(X) = \dfrac{M_{a2x}}{M_{a2}} = \dfrac{x}{L} = X$ — uniform distribution;

(2) $\varphi(X) = \dfrac{M_{a2x}}{M_{a2}} = \left(\dfrac{x}{L}\right)^2 = X^2$ — slow increasing of M_{a2x} at small values of x and rapid increasing of M_{a2x} at large values of x;

(3) $\varphi(X) = \dfrac{M_{a2x}}{M_{a2}} = \left(\dfrac{x}{L}\right)^{1/2} = X^{1/2}$ — rapid increasing of M_{a2x} at small values of X and slow at large values of X.

Consider Fig. 6 where curves $1/\phi_x = f(X)$ are also given for these cases. The most favourable distribution at $\phi = 1$ is uniform (case 1): the overall efficiency is maximum. In case 2 burning delays because of
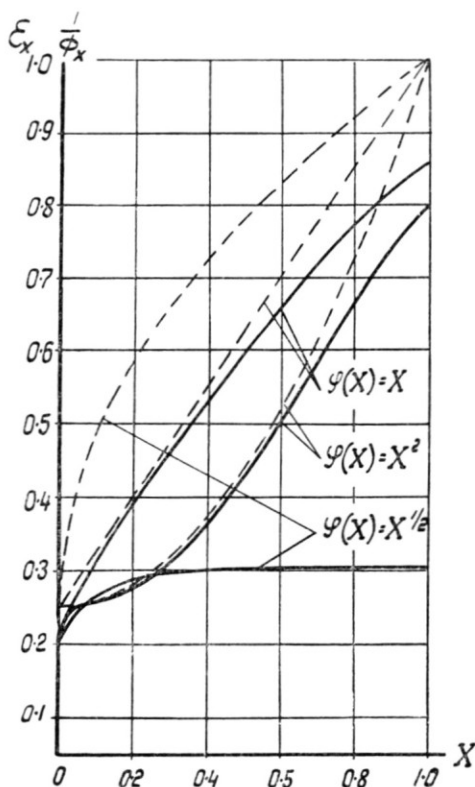

FIG. 6. Plots of ε_x and $\dfrac{1}{\Phi}$ along the secondary zone.

$\Phi = 1$; $b = 0.25$; $\beta = 0.8$; $P_c = 1.5$ atm; $V_c = 1.0$ m³/sec; $T_c = 400°$K.

$$- - - \quad \frac{1}{\Phi_x}$$

$$\text{———} \quad \varepsilon_x$$

slow admission of the secondary air into the fore part of the flame tube; in the tail part of the flame tube chilling influences efficiency because of the rapid admission of the secondary air. For case 3 burning ceases even at a small distance from the primary zone as a result of rapid admission of the secondary air.

At large values of $1/\phi$ (Fig. 7) for case 2 combustion efficiency is higher than for case 1. Explanation is that at large values of $1/\phi$ (and consequently at large values of $1/\phi_1$, because $1/\phi_1 = b1/\phi$), when $\varepsilon_1 = \beta 1/\phi_1$ has high value, the mixture leaving primary zone contains a small amount
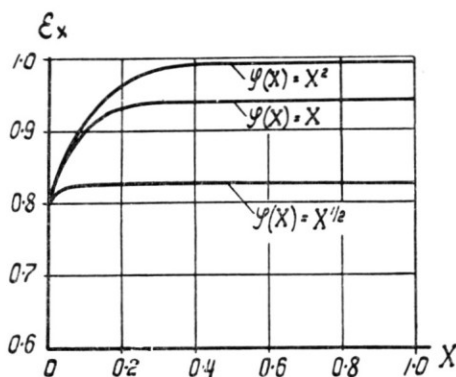

FIG. 7. Plots of ε_x along the secondary zone.
$\Phi = 0.25$; $b = 0.25$; $\beta = 0.8$; $P_c = 1.5$ atm; $V_c = 1.0$ m³/sec; $T_c = 400°K$.

of fuel, which results in the small reaction rate. Therefore in order to get high combustion efficiency in the secondary zone it is expedient to add the secondary air at first slowly to ensure the possibility of the completion of the reaction which is going on at a very slow rate.

Figure 8 shows curves illustrating relationship between overall efficiency ε and $1/\phi$ for these three cases. The comparison of curves 1 and 2 shows that with the delayed air admission at the fore part of the secondary zone and rapid admission at the tail part (case 2), the value of ε falls in rich mixtures and rises in lean mixtures.

For a very intense air admission just behind the primary zone (curve 3) the combustion process in the secondary zone ceases and therefore the corresponding curve $\varepsilon = f(1/\phi)$ reflects mainly the dependence of combustion efficiency in the primary zone ε_1 on ϕ_1.

The same explanation can be given for the influence of the relative part of the primary air b on ε.

One can derive from the proposed scheme that it is possible to increase considerably combustion efficiency (under unfavourable conditions) by using fuels with larger reactivity. Results of refs. 3 and 4 confirm this conclusion. In ref. 3 the dependence of ε on the mean velocity of flow

was established at low air pressure and temperature for two fuels (n-heptane and isoctane). These fuels have the same boiling temperature but differ in values of laminar flame velocity U_n. According to the theory of laminar flame the chemical reaction rate $w \propto U_n^2$. Therefore one is to suppose that for securing $\varepsilon = $ const. the ratio of the mean flow

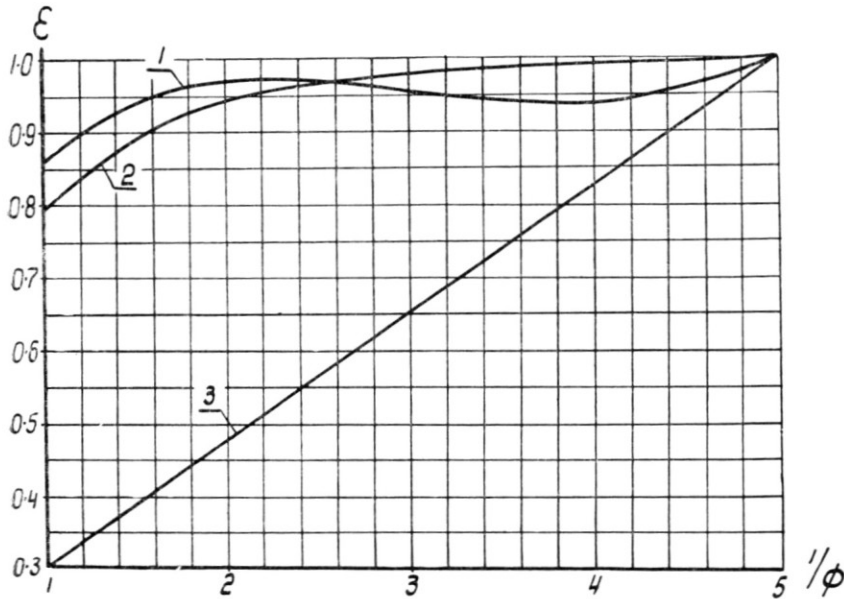Fig. 8. Dependence of ε on $1/\Phi$ for various secondary air distributions.
$b = 0 \cdot 25$; $\beta = 0 \cdot 8$; $P_c = 1 \cdot 5$ atm; $V_c = 1 \cdot 0$ m²/sec; $T_c = 400°$K.
$$1 - \varphi (X) = X$$
$$2 - \varphi (X) = X^2$$
$$3 - \varphi (X) = X^{1/2}.$$

velocities must equal the ratio of the chemical reaction rates. Analysis of data given in ref. 3 shows that this does occur in experiment. In ref. 4 combustion efficiency ε was determined for various gas fuels in a gas turbine combustion chamber under pressure below atmospheric. It was shown that, in accordance with the values of the reaction rate, ε rises with transition from propane to ethylene and then to hydrogen.

Thus, the scheme based on the fact that under unfavourable burning conditions the combustion efficiency begins to depend on the chemical reaction rate, gives the explanation of the influence of the operational regimes (ϕ, P_c, T_c, V_c), design factors (D, $f(X)$, $b,L/D$ and so on) and physico-chemical factors on combustion efficiency.

In conclusion, it should be noted that the small difference in the performance of the chamber on main operational regimes with injecting

liquid and preliminary vaporized fuel allows not to take into account in the first approximation the influence of atomization and evaporation processes in an attempt to find the generalized relationship between ε and various parameters. In other words, one can use equation (1), derived by assuming the absence of the influence of the processes mentioned above.

By a generalization of the theoretical data it was shown that one can express ε as a function of the so called loading parameter $M_a/P_c^{m_1}T_c^{n_1}D^3$, where values of m_1 and n_1 must be found from experiment. Then a treatment was made of the experimental data obtained by testing series of the geometrically similar combustion chambers with injection of both liquid and vaporized fuels. The range of air temperature was 10–500°C, of air pressure 0·4–3·0 atm, of mass flow 0·05–7·4 kg/sec; the flame tube diameter was varied from 75 to 270 mm.

The distinct relationship was obtained between ε and the loading parameter $M_a/P_c^{1.25}T_cD^3$. This relationship makes it possible to establish sizes of the combustion chamber for the given values of the air parameters or to find ε approximately for a given chamber under various conditions.

REFERENCES

1. KWASNIKOW, L. A., TARASOW, E. W. and SHAKCHURIN, S.I., Development of a Combustion Chamber for Elevated Gas Temperatures, Proc. of High learning, *Aviat. Engng*, N 4, 1958.
2. Sixth Symposium (International) on Combustion. N.–J, Reinhold Publ. Corp., 1957.
3. OLSON, W. T., CHILDS, J. H. and JONASH, E. R., The Combustion Efficiency Problem of the Turbojet at High Altitude. *Trans. ASME*, Vol. 77, N 5, 1955.
4. NOREEN, A. E. and MARTIN, W. T., A Generalized Presentation of Gas Turbine Combustor Performance, ASME Paper N 57, GTR-5, 1957.