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## The Propulsive Duct

**A Theoretical Approach to Assessing the Thermodynamic Process Within the Combustion Chamber of the Propulsive Duct, an Examination of the Potential of the Duct with Special Reference to the Application of Feedback and Spark Discharge Techniques**

By C. E. Tharratt, F.S.E., F.R.Ae.S., F.B.I.S.

(Concluded from p. 371 of the December 1965 issue)

### PART III

#### POTENTIAL

In its present form the propulsive duct has two distinct advantages

- Simplicity
- High power to weight ratio.

It also has three disadvantages

- High specific fuel consumption
- Low power per unit area
- High noise level.

In this section it will be shown that with suitable development the disadvantages can be removed and the propulsive duct will be shown to offer a potential far exceeding that of other forms of air breathing prime mover.

The most important requirement, however, is to devise a method of substantially raising the level of working peak pressures for it is shown in FIG. 7a that above  $\xi_0/L = 0.6$  the thrust is approximately equal to

$$F \approx \frac{1}{2} P_{\max} \dots \quad (19.1)$$

Chemical fuels obviously set a limit to the maximum thrust attainable, due to the relatively long burning time of the fuel particles; the effect of burning time on peak pressure was clearly demonstrated in FIG. 31. With the aid of Eq. (13.15) it can be shown that even the most violently reactive explosives cannot produce the peak transient pressures necessary. Since, theoretically, there is no limit to the thrust that can be developed providing the peak transient pressures can be obtained, other methods of adding the heat must be explored.

The most promising method is to heat the working medium by electrical means using spark discharge techniques. This also permits synchronous or programmed injection of heat to banks of ducts and eliminates the stochastic combustion process associated with chemical heating in the higher frequency regimes.

For an electrical spark to bridge the gap between two hemispherical electrodes there are two main though inter-related requirements, namely, the voltage must be high enough and the presence of ions is necessary to permit the initial current flow. Thereafter the high local gas temperatures gives rise to an increased number of ions, the current increasing in an avalanche effect until enormous currents eventually flow in the ionised plasma between the electrodes.

Spark discharge techniques are highly developed for the high-power modulators used in radar where in some applications Trigatrons are used for triggered spark gaps discharging a 2 MW., 1μ sec., 7.5 kV. pulse at

1,000 pulses/sec., see Refs. (12) and (13). For the duct application the power handling capability of the Trigatron would have to be extended but there appears to be no unsurmountable difficulties. A number of discharge electrodes may be arranged in series as shown in FIG. 41, and this is a particularly convenient arrangement as in the duct application they may be strategically located in the energy injection zone to spread the heating area. The trigger is integral with one of the electrodes and its purpose is to produce sufficient ions to permit the main electrodes to discharge at the correct time interval.

To calculate the power of each discharge we obtain the energy required per cycle using the method outlined in an earlier section; convert this into watts, then the power required per cycle is equal to the peak power  $P_w$  of discharge times the length of discharge  $t_e$  sec.

$$\therefore \text{watts/cycle} = P_w t_e$$

and the average power for  $n_f$  cycles

$$P_{av} = P_w t_e n_f \text{ watts} \dots \quad (19.2)$$

where

$$t_e n_f = \text{duty cycle}$$

and, as stated earlier, to obtain an efficient means of generating the peak transient pressures the energy must be injected in less than 10 per cent of the expansion cycle, thus the duty cycle is <0.025 and in general

$$P_w > 40 P_{av} \dots \quad (19.3)$$

We are now in a position to note an exciting possibility for, provided the necessary peak power  $P_w$  can be passed, the pulse duration  $t_e$  may be made very short and extremely high operating frequencies become possible, with a proportional reduction in chamber length and, consequently, weight. For instance, if  $t_e = 1\mu$  sec., near constant-volume heating is possible up to 25 Kc/s and, at these frequencies and the noise levels discussed earlier, operation beyond the audible limit can be achieved. This may not be wholly realizable in practice, however, since the electric spark is, in fact, a white noise generator. It is quite clear though that the application of spark discharge techniques offers a greater thermal efficiency, higher peak transient pressures and the promise of greatly reduced noise levels, and these are important and worthwhile features.

Having shown that higher peak pressures, and therefore thrust, is possible we may now examine the true potential of the duct. The simplest method is by giving an example; it should be noted that one basic assumption will be made: it is assumed that the temperature problem can be solved.

## PROPELLIVE DUCT

Consider the duct in FIG. 43, it has an  $L/D=0.11$  where  $L=0.6$  in. and  $D=5.4$  in. If it is designed for a thrust  $F_0$  of 3 atmospheres the peak transient pressure is 36 atmospheres

$$\therefore P_{\max}/P_0 = 36 = T_{\max}/288 = (T_{\max}/T_1)^{\gamma/(\gamma-1)}$$

and the mean temperature  $T_1=3,730$  deg. K.; note that a reduction of 13 deg. is obtained for each degree reduction of the inlet temperature, this suggests that refrigeration may be an advantage. Using this temperature,  $\gamma=1.4$  and the chamber length  $L=0.6$  in., the operating frequency is approximately 20 Kc/s; the thrust is approximately 1,000 lb., and from FIG. 11 the specific fuel consumption should be less than 0.6 lb./hr./lb. thrust or, converting this into watts  $P_{av}=3.22$  MW., and if the energy is injected in one-fortieth part of the operating cycle we require to discharge a 129 MW.,  $1.25\mu$  sec., 105 kV. pulse at 20 Kc pulses/sec. The voltage level is determined by the dimensions of the discharge gap, Ref. (14), which in this particular configuration is approximately 4 cm.

It is proposed that the duct perimeter should house twelve electrodes each positive with respect to the central hemisphere. The radius of this and the longitudinal profile of the outer electrode being chosen to suit the discharge gap.

As the working temperature is increased and the thermal problems become more severe it should be possible to use the high electrostatic voltages to prevent the highly ionised plasma making contact with the perimeter.

The geometry of the duct, FIG. 43, also appears suitable for the application of the feedback principle, Eqs. (18.11) to (18.13). Therefore clustering 19 units as shown in FIG. 42 and, assuming an incident pressure of 0.7 lb./sq. in., the thrust increases from  $F_0=3$  atmospheres to  $F=9$  atmospheres (approx.), the gross thrust of the cluster being 57,000 lb. The input power, of course, has only increased by the number of ducts, therefore, the source power required is 61.2 MW. and the effective specific fuel consumption, in terms of FIG. 11, reduces to 0.2 lb./hr./lb. thrust. The electrical power for this type of application can, logically, only be derived from atomic power units or highly developed fuel cells.

The frequency of operation was earlier determined as 20 Kc/s, with feedback this will increase, now the human ear is a non-linear device with a frequency response which rapidly falls away above 15 Kc/s, see Richardson, Ref. (11). Thus the ear cannot readily detect a 20 Kc/s note below abnormal power levels. On the other hand, the drum acts as a rectifier to sense peak power levels and at levels of approximately 120 (db) (above  $10^{-16}$  watts/cm<sup>2</sup>) the nervous system senses pain. This is the so-called Threshold of Feeling.

Choosing an arbitrary margin of 20 (db) below the Threshold of Feeling an observer would neither 'hear nor feel' pressure pulses from a duct operating in the region of 20 Kc/s or above at or beyond a radius from the source equivalent to a power level of 100 (db) phons. Therefore, with 100 (db) phons as the upper level we note from FIG. 37 that, based on a radius  $r_0$  of 2.7 in., a single duct is apparently silent outside a radius of, approximately,  $1.15 \times 10^3$  ft. A cluster of 19 ducts adds a further 12.8 (db) and under these conditions the radius of silence is approximately  $2.3 \times 10^3$  ft.

Note, however, that in the practical case an electric discharge is effectively a 'white-noise' generator, therefore there will be a spectrum of frequencies present and, depending on the frequency and power level, these most probably will be heard.

On the other hand, the fundamental frequency, which contains most of the energy, will not be 'heard' outside the radii stated above, which should now be regarded as 'radii' of subjective silence.

This amply demonstrates the potential of the duct which, by its small size and high power-weight ratio, lends itself to all forms of transport; especially to aircraft where the adoption of the feedback principle permits

operation at the fringe of space where the atmosphere is still a tenuous medium or, conversely, at low level in V.T.O.L. applications since the units may be installed in areas of limited space within the airframe. Its application to ship and similar low-speed transport should not be overlooked for, unlike most prime movers, the duct is particularly well suited for developing its maximum thrust under static or near static conditions.

The operation of the duct in the regimes of subsonic and supersonic flight offers a significant technical challenge in the fields of aero and thermo dynamics; particularly in the area of intake design. It was stated earlier that the valve of the conventional duct failed to operate at air velocities in the region of  $M=0.6$ , because the ram pressure exceeded the combustion chamber pressure. With spark discharge heating, the combustion pressures are more than adequate to cope with foreseeable ram pressures, therefore, this problem is no longer a barrier. Nor is there an area ratio problem, for this was a limitation only when conventional fuels were used. Thus, there is scope for considerable ingenuity and technical skill in manipulating the phasing of shock fronts throughout the resonant system.

Operation at supersonic velocities requires a modified approach to that used hitherto. The chief problem is the ram pressure, and there are two possible approaches to overcome this. First, the propulsive duct intake could be designed to have a pressure drop across it such that the ram pressure is effectively dissipated. This is a wasteful method and, unless a mechanically complex intake valve is installed, there is the possibility that the propulsive duct will only operate effectively at a predetermined design point. Second, the ram pressure could be made to contribute to the thrust output. To accomplish this it is necessary to devise a method for automatically increasing the mean combustion chamber pressure to the level of the ram pressure. One such method is outlined in the following example.

Consider an engine travelling at a height of 70,000 ft. with an airspeed of  $M=3$ ; the local ambient pressure is 0.64 lb./sq. in. absolute. FIG. 44 illustrates an engine configuration that consists of an aerodynamic intake and a propulsive unit. The latter takes the form of a series of annular propulsive ducts, each using spark discharge heat injection. Air flowing into the intake passes through two oblique shock fronts and is decelerated to  $M=1$ . The intake area is determined by the air consumption requirements of the propulsive ducts. During the heat injection period, the air flow into the propulsive ducts is arrested and the full total head pressure,  $P_t=15.2$  lb./sq. in. absolute, is developed, note that the free stream ram pressure is 23.7 lb./sq. in. absolute. The shock fronts do not break down, however, due to the very high combustion frequency and the dampening effect of the air cushion formed between the downstream shock front ( $M=1$ ) and the propulsive duct intakes.

Assume now that in some manner, as yet unspecified, the local ambient pressure at a given propulsive duct outlet, i.e. at  $x=L$ , is raised to the total head pressure  $P_t$  within the intake. The thrust, being proportional to ambient pressure, will increase by a factor of  $15.2/14.7=1.034$  over that obtained at sea level. Following spark discharge heat injection, a

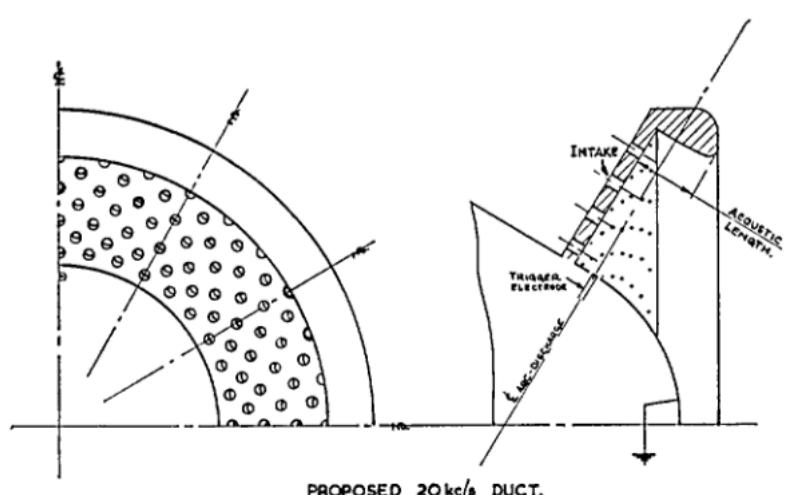


Fig. 43.

pressure pulse travels radially away from the combustion chamber outlet until, at a radius  $r$ , it has decayed to  $P_t$ . If another duct outlet is located at  $r$  and the pulse is timed to reach  $r$  at  $nct = \pi/2$  then both inlet and outlet of this second duct will simultaneously experience  $P_t$  at the correct time interval. In this manner, the conditions required by the operating cycle can be maintained. A similar sequence of events occurs from the second duct to the first duct, thus satisfying the requirements of the original assumption.

For this condition to be possible, the following relationship must be satisfied, see Eq. (18.7)

$$(1 + \partial\phi/\partial r)^{-n} = 1$$

or

$$\partial\phi/\partial r = 0$$

thus, see Eq. (5.5a)

$$(nL)/r \sin n(r - r_0 - ct) + L/r^2 \cos n(r - r_0 - ct) = 0$$

let

$$r = 2r_0$$

$L = kr_0$  where  $k$  is a constant

$$nct = \pi/2$$

then

$$K/2(nL) = \tan(\pi/2 - (nL)/K)$$

the solution is

$$(nL)/K = 1.165$$

$$\therefore L = (nL)r_0/1.165$$

or

$$L/D = (nL)/2.33$$

if we assume that  $\xi_0/L = 0.8$  is possible, then from FIG. 6  $(nL) = 0.566$  radians.

The peak pressure for the foregoing conditions is obtained from Eq. (4.10)

$$(P_{\max}/P_t)_{x=0} = (P_{\max}/15.2)_{x=0} = 30$$

$$P_{\max} = 456 \text{ lb./sq. in. absolute}$$

and thrust

$$F_0 = P_{\max}/12 \text{ lb./sq. in. from FIG. 7a}$$

$$= 38 \text{ lb./sq. in.}$$

note that  $F_0$  is 'above' the total head pressure datum  $P_t$  and the sum of these minus the free stream ram pressure is a simplified estimate of the available thrust per sq. in. to overcome vehicle drag and other losses at  $M=3$ .

For the given conditions the  $L/D = 0.242$  and, with the temperature involved, operation in subjective silence should be possible. It is important to note that to maintain a transfer of energy from one duct to another, it is essential that the  $L/D$  ratio be kept as low as possible. This ensures a semi-omni-directional exhaust flow. As the  $L/D$  ratio increases, the gas flow becomes more uni-directional, thus reducing the efficiency of energy transfer to closely situated ducts.

From this example it is obvious that the analysis has been simplified for the purpose of illustration, and detailed manipulation of the basic equations is necessary before the full performance spectrum can be analysed. Even with this limitation, it is clear that operation at supersonic speeds is possible. However, the true potential of the duct depends upon two factors, namely, a solution to the thermal problems and the development of an efficient, mobile source of electrical power.

#### CONCLUSIONS

In the preceding sections an attempt has been made to lay down the foundations for a rational explanation of the thermodynamic processes in duct operation and it has been shown that the theory is closely followed in practice.

The method of analysis, based essentially on the validity of Eq. (4.4), also permits a theoretical examination of the thrust per unit area, waveform distortion, specific fuel consumption, air consumption, area ratio, the combustion phase, duct geometry and noise level.

A further theory is put forward for the *modus operandi* of the aerodynamic valve the salient features of which appear to be confirmed by practical test.



The closeness of practice to theory encourages an extrapolation into the higher thrust regimes and this leads directly to the application of feedback techniques and it is shown that, providing the temperature problem can be overcome, theoretically, any desired thrust level per unit area is possible, with a corresponding reduction in specific fuel consumption.

To permit the use of feedback techniques it has been shown that a departure from chemical fuels must be made; the most promising method of injecting the heat being by electric spark-discharge techniques. This leads directly to the possibility of operation at very high frequencies beyond the audible range and the potential for operation in subjective silence.

The high power requirements of electrical energy injection lead naturally to the marriage of the duct to the generation of electrical power by atomic means, or fuel cells, and this, coupled with the potential for near silent operation, is extremely attractive.

#### ACKNOWLEDGMENTS

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Thanks are also due to Mr M. J. Brennan, formerly Chief Designer, *Saunders-Roe Ltd.*, for introducing the author to the intriguing design and development problems of the ducts outlined in Ref. (9). The nature of the project permitted only rudimentary measurements of thrust, fuel flow and frequency, it was not possible to record and investigate the waveform under various operating conditions. The records taken eight years earlier by Wolfe and Luck of the R.A.E. were therefore invaluable, and it is possibly true to say that this paper is the outcome of a desire to correctly interpret the waveforms recorded by them and reproduced in FIG. 32.

All researchers in this field have had an instinctive feeling that the duct had a great potential and although their reports have been of little direct value the overall effect has been to convince the author that there was a need for a theoretical analysis. Thanks are therefore due to the unknown workers for their snippets of information.

The opinions, and particularly the assumptions, expressed herein are entirely those of the author, and are not necessarily shared by any of the above organizations or individuals.

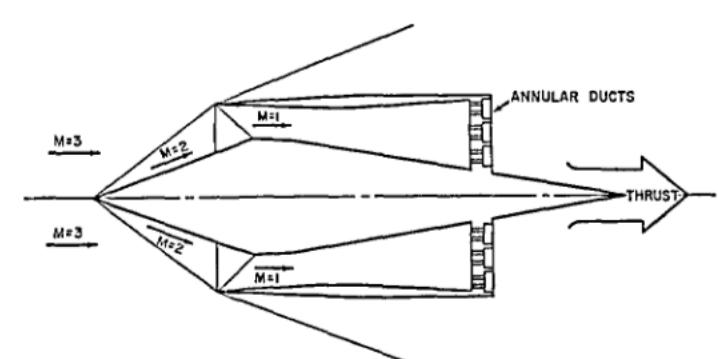


Fig. 44.