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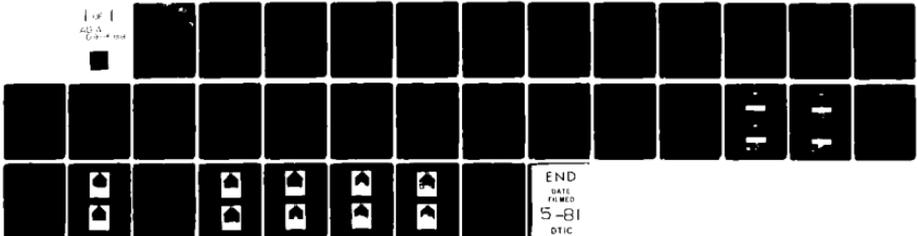
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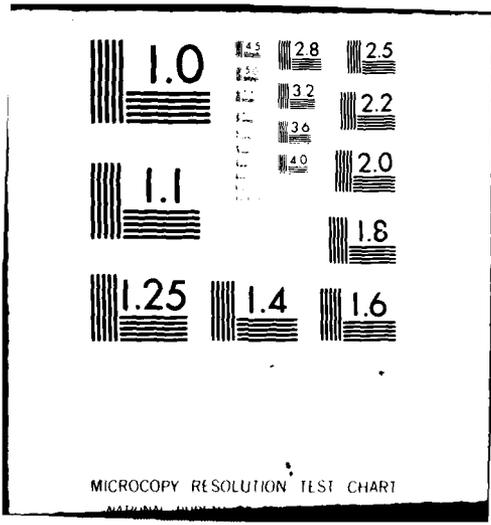
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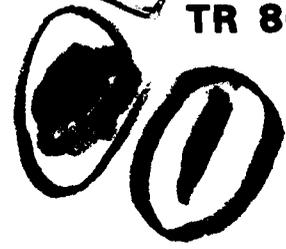


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**HIGH-SPEED CINEMATIC STUDIES OF
WATER VAPORIZATION PHENOMENA
IN ELECTROTHERMAL HYDRAZINE
THRUSTER SIMULATIONS.**

by

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HIGH-SPEED CINEMATIC STUDIES OF WATER VAPORIZATION PHENOMENA
IN ELECTROTHERMAL HYDRAZINE THRUSTER SIMULATIONS

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W. G. Grenham

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SUMMARY

→ Tests of prototype electrothermal hydrazine thrusters (EHTs), intended for satellite attitude and orbit control, revealed anomalies in performance, attributed to problems in vaporization. The process of vaporization was studied by high-speed cinematography, with water substituted for hydrazine in models of the EHT. The results of the flow visualization research are described, and it is concluded that Leidenfrost film-boiling effects inhibited vaporization and affected the performance of the thrusters. ↗

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1 INTRODUCTION

Electrothermal hydrazine thrusters (EHTs) are small, monopropellant propulsion devices, currently under development for attitude and orbit control of satellites. Thrusters used for attitude control normally operate in a pulsed limit-cycling mode, in which the accuracy of the control system is dependent on the minimum impulse capability¹. It is necessary, therefore, within practical limitations, that the thrust level and minimum pulse duration be made small. For example, a specification² for an EHT suitable for use on a European communications satellite called for a maximum thrust in the range 200-500 mN and a minimum impulse capability of 5 mN s, implying pulse durations possibly as low as 10 ms. The EHT offers a potential advantage over existing low thrust pulsed catalytic hydrazine thrusters in that these minimum impulses may be achieved at a higher exhaust velocity or specific impulse³ (*ie*, with greater propellant economy).

In the electrothermal hydrazine thruster the catalyst bed is replaced by a suitable electrically powered heat exchanger. At the expense of some extra watts of electrical power, known limitations of catalytic thruster life⁴ (associated with catalyst erosion and poisoning by the hydrazine decomposition products), which have been only partly overcome by catalyst-pack heating, may be completely eliminated. So, with provision of suitable long-life heaters, EHTs should be capable of delivering a much greater number of pulses than comparable catalytic thrusters.

To gain the greatest advantage from the use of EHTs (or for that matter from any attitude and orbit control thruster) it is essential that the necessarily small impulse values are achieved efficiently. Since the thrust coefficients of conventional convergent-divergent nozzles have been shown^{5,6} to degrade with lower plenum pressures (due to boundary-layer growth at low Reynolds numbers) it is important that the rise and decay times of the plenum pressure should be minimised. The nozzle will then operate close to its design pressure, even for short duration pulses. The dwell time of the propellant in the decomposition chamber will vary with pressure so for optimum dissociation of the propellant to avoid degradation of specific impulse, it is important that the thruster exhibit stable behaviour without excessive pressure excursions.

In principle, to achieve short duration, stable pulses, the decomposition chamber volume must be minimised and within its confines, the propellant must be vaporized and decomposed as rapidly as possible. The ideal, overall decomposition rate is equal to the mass flow rate of fuel into the decomposition chamber; under this condition the plenum pressure would always be stable and the pulsed performance of the thruster would be optimised. Unfortunately, for thrusters smaller than 500 mN, such a state has been extremely difficult to achieve. The conventional means of ensuring rapid decomposition or combustion, employed in larger rocket motors⁷ and other combustion processes involving liquid fuels⁸ is to atomise the propellant. In the EHT however normal atomising methods are not appropriate due to the imposition of a lower limit to injector dimensions to avoid blockage.

An RAE prototype thruster is shown in Fig 1, attached to its propellant flow control valve. It was designed to deliver a thrust in the steady state, of 200 mN at a supply

pressure of 1.4 MN/m^2 (14 bar). In common with most, if not all, current hydrazine thruster systems, there was a requirement that the EHT operate from an unregulated or 'blow-down' supply system, in which the pressure would fall predictably from 22 bar to 5.5 bar as the propellant was used during the useful life of the spacecraft.

The liquid monopropellant, anhydrous hydrazine, is delivered to an on-off electromagnetic flow control valve from a pressurised supply. The control valve shown attached to the thruster in Fig 1 is of a configuration developed by RAE⁹. Valves of this type have been manufactured by British Aerospace Dynamics Group, and have undergone qualification testing at RAE¹⁰. The valve is operated by electrically energising the solenoid, which retracts the armature, opens the valve, and allows hydrazine to flow through the small bore injector tube (typically 0.125 to 0.15 mm diameter), and into the thruster body. On switching off the solenoid current the valve closes under the action of a return spring.

In these prototype thrusters which were used for ground level testing only, the body was made of stainless steel (S130B) and was heated electrically by means of a 6 W ceramically insulated, sheathed element, coiled around and brazed to the outside of the body.

The internal heat exchanger matrix consisted of a series of sixty 52 mesh platinum gauzes compressed to a length of 5 mm, with a single rigid mesh support, downstream, of stainless steel. The gauze-pack heat exchanger served the purpose of supplying sufficient thermal energy to vaporize propellant, and to initiate the decomposition reaction of hydrazine. Some of the thermal energy released by the exothermal decomposition was then utilised to sustain the reaction.

With reference to Fig 1, the volume between the injector tube exit and the gauze-pack surface will be referred to as the 'head-space'. The internal diameter and the length of the head-space, in this configuration, were both about 5 mm. Downstream of the gauze-pack, a smaller 'tail-space' formed the plenum, leading to a conventional convergent-divergent nozzle. The nozzle throat diameter was 0.45 mm, and the area expansion ratio was 50:1 with a nozzle divergence half-angle of 15° . A dynamic measure of plenum pressure was obtained and recorded by means of a suitable, low volume, pressure transducer attached to the tapping into the tail-space. This gave an indication of the internal performance of the thruster.

Tests of the prototypes confirmed results reported by HSD¹¹ for similarly configured EHTs and showed that there seemed to be little problem in steady-state operation; however, when operated in the pulsed mode, with pulse durations of 1 second or less, the performance of the thrusters was far from adequate. This was especially so during the first few pulses of a train.

A 'typical' train of pulses is depicted in Fig 2. This demonstrates the form of the starting transient and the fairly random pressure spiking effects which occurred. It can be seen that the plenum pressure profiles exhibited some characteristic behaviour: the pressure rose rapidly but then became inhibited or suppressed, before rising further to a quasi-steady level on which the pressure spikes were superimposed. The characteristic dip

or levelling during the pressure rise will be referred to as the 'plateau region'. Long duration pressure decays were also observed, though these are not evident from the Figure.

The form of the first pulse characteristic was influenced by the supply pressure and by the initial holding temperature. Fig 3 shows an example of the variation in first-pulse starting characteristic caused by varying the propellant supply pressure, while Fig 4 illustrates the effect caused by variation of the initial holding temperature. It may be noted from Fig 4 that there appear to be two plateau regions, the first becoming increasingly significant as the temperature is raised, while the second, which is separated from the first by a peak in the plenum pressure, is only significant at the lower temperatures.

The flow visualization studies described in this Report were directed towards the understanding of this behaviour. Experiments involving high-speed cinematography were carried out to gain an improved knowledge of transient vaporization phenomena, so that means of improving the pulsed performance of the prototype EHT might eventually be derived.

2 THE PHILOSOPHY BEHIND THE FLOW VISUALIZATION RESEARCH

2.1 The possibility of vaporization-rate dependence

The behaviour of the prototype thrusters was inexplicable in all but a very general sense; it was however realised that the anomalies described in section 1 must have resulted from one, or more, of the following:

- (i) variations of the mass flow rate into the decomposition chamber;
- (ii) fluctuations in the vaporization rate of propellant within the decomposition chamber;
- (iii) fluctuations in the decomposition rate of vaporized propellant within the thruster.

To determine a means of improving the design it was necessary to study, and hopefully to isolate, the short-lived phenomena that occurred within the thruster. The alternative, of performing a great number of empirical tests while varying particular thruster parameters or configurations, was considered to be inadequate. Even if an improvement were achieved by this entirely empirical method, sufficient understanding of the reasons would not be available to aid scaling for different thrust levels.

It was reasoned that, since thermal decomposition of the propellant occurs mainly in the vapour phase¹², although undoubtedly influenced by the temperature and the geometry of the thruster decomposition chamber, the decomposition reaction was likely to be vaporization-rate dependent, especially as the injector was not designed to atomise the propellant, and therefore a study of vaporization phenomena would be worth while. It is well known¹³ that heat transfer rates during film-boiling are drastically lower than those during nucleate-boiling, and a study of some of the literature concerning the Leidenfrost phenomenon^{14,15} suggested the possibility that propellant vaporization, and hence decomposition rate, was reduced by film-boiling effects.

2.2 The Leidenfrost phenomenon and the need for experimental study

The Leidenfrost phenomenon was named after the 18th century medical doctor who first studied it¹⁶. Traditionally it is concerned with the film-boiling of small liquid masses on hot surfaces.

As the temperature of a heated surface is raised above the saturation temperature of the liquid (the 'boiling point' if the experiment is performed at normal atmospheric pressure), the vaporization rate of a droplet placed on the surface increases during what is generally termed the nucleate-boiling régime. Under this condition the liquid wets the surface and there is good thermal conduction into the liquid from the surface. Vapour generation is from nucleation sites, *ie* small imperfections in the heated surface. At higher temperatures, however, when the change from nucleate to film-boiling occurs, the vaporization rate falls dramatically. At temperatures above the transitional zone heat transfer from the plate is such that vaporization occurs across the whole interface, with the result that the droplet may be suspended above the surface on a cushion of vapour. The result is a reduction in the rate of heat transfer to the liquid. The lowest value of surface temperature at which stable film-boiling of a droplet is observed under a given set of experimental conditions is called the Leidenfrost point¹⁴ and coincides with the minimum heat transfer condition.

Fig 5 shows the form of the vaporization rate/excess temperature characteristic for water. The curve is based on experimental data on the variation of total vaporization time of uniform droplets with excess temperature presented in Ref 17. The excess temperature ΔT is defined as the difference between the local temperature T_p of the plate, and the saturation temperature T_s of the liquid such that

$$\Delta T = T_p - T_s .$$

Fig 5 may be compared with a similar curve showing heat flux against excess temperature for boiling on a platinum wire, presented in Ref 13 and elsewhere. Although no data was available for hydrazine, other liquids (including flammables such as benzene, n-octane, kerosene and ethanol) are known to demonstrate a similar form of behaviour to that of water^{14,17}. The gradual rise in heat transfer rate after the Leidenfrost transition is caused by the increase of radiant heat transfer to the droplet with increasing surface temperature¹³.

Under a given set of conditions the initial size of the droplets appears to have little effect on the measured Leidenfrost point¹⁴. The method of deposition of a droplet onto a surface does, however, have a marked effect on the observed Leidenfrost point and on the heat transfer rates. It has been shown¹⁵ that for oblique incidence on to flat plates, the normal component of velocity is the important factor. While it is known that good repeatability can be achieved in experiments concerning Leidenfrost film-boiling on flat plates, there is no unique value of the Leidenfrost point for a given liquid¹⁴. It would appear that this may be accounted for by differences in experimental technique, surface texture, and even between different experimenters using the same apparatus.

Given these uncertainties concerning Leidenfrost phenomena when confined to flat plates it was clear that some experimental work would be needed before reliable conclusions

could be reached about propellant vaporization in EHTs. Tests were proposed, therefore, in which the vaporization phase of the propellant reaction was isolated by the substitution of a suitably inert fluid and as the most convenient method of differentiating nucleate- and film-boiling was by visual observation, *ie* by the 'wetting' or 'non-wetting' of the heated surfaces, it was decided to use a flow visualization technique.

2.3 The choice of water as a hydrazine substitute

Water was chosen as a suitable fluid for the tests as it had a number of advantages. Firstly, its total non-flammability meant that the vaporization effects could be isolated by the exclusion of decomposition and/or combustion. Secondly, with the possibility of combustion removed and in the absence of any toxicity problem the experiments could be carried out in atmosphere under normal laboratory conditions, which meant that the experimental requirements could be greatly simplified. Thirdly, many of the physical properties of hydrazine and water are similar at least to a first approximation. The most obvious of these is the boiling point, that of anhydrous hydrazine at normal atmospheric pressure being 113.5°C which is close to that of water. They are both colourless liquids with low vapour pressures. Their respective densities, surface tensions, viscosities, and specific heat capacities are similar. A major difference in relevant physical properties between the two fluids, however, apart from their chemical differences and flammabilities, is between their latent heats of vaporization. Water, possessing a higher value of latent heat would, if exposed to the same conditions as hydrazine, require more thermal energy to effect a phase change. It was possible, however, to take this into account in interpreting results.

2.4 The need for high-speed cinematography

In designing the experiments it was realised that the processes of injection, vaporization and exothermal decomposition were highly interrelated: in steady-state operation a proportion of the thermal energy derived from the decomposition reaction was required to be fed back to sustain vaporization. This was because the sensible heat in the thruster body was insufficient to sustain vaporization, and the steady electrical power supplied to the thruster heater was of the order of a twentieth of that required for continuous vaporization. Dynamic tests with water therefore would have most relevance to the starting transient, when vaporization would depend primarily on the thermal energy stored in the thruster body and gauze matrix.

Since the events to be studied were transitory phenomena of short duration, a visual recording technique employing high-speed cinematography was necessary.

3 FLOW VISUALIZATION EXPERIMENTS

3.1 Series 1: injection on to heated gauzes

The object of the first series of flow visualization tests was to establish whether film-boiling effects could be observed in the behaviour of water injected on to heated gauzes and, if so, to ascertain the temperature régime in which they became significant. This was to be done by filming the transient behaviour of water injected towards a suitable gauze-pack, the gauzes being heated over a range of initial temperatures.

The apparatus consisted of a pack of five stainless steel gauzes as shown, diagrammatically, in Fig 6. The gauzes were clamped at either end to thermal sources to which electrical heaters were attached. The starting temperature for each test was determined from a thermocouple spot-welded to the lower gauze. The injector had a bore of 0.15 mm diameter and was mounted with its exit plane approximately 4.5 mm from the uppermost gauze. Water was delivered to the injector from a pressurised supply, via a suitable electromagnetic valve.

The photographic set-up for the experiment is shown in Fig 7. The injector and gauzes were back-lit using a tungsten filament bulb and an optical condenser. Some pre-test runs were carried out and established that a filming speed of 5000 frames/second was suitable. With this framing rate, the effects of single pulses of 100 ms duration could be accommodated on 100 feet of 16 mm ciné film, allowing for acceleration time of the film in the camera, prior to the event. A time resolution of 0.2 ms was therefore achieved. An accurate measurement of elapsed time was obtainable from the processed film record as a time-base unit was employed giving 1 ms time marks on the edge of the film. An event mark was incorporated, being triggered simultaneously with the valve driving unit. The valve was triggered from the camera once the pre-selected running speed had been achieved.

A series of test runs was performed within a gauze initial temperature range of 293-770 K, with single pulses of 100 ms duration. The steady-state flow rate through the capillary bore injector was 0.17 ml/s. A limit imposed by the thermal losses from the experiment precluded tests at temperatures greater than 770 K.

Figs 8 to 11 show some selected still frames obtained from the processed high-speed ciné films. The times quoted relate to the instant of fluid emergence from the injector tip and therefore exclude valve operating and injector transport delays. The films showed that with moderate initial temperatures, between 373 K (100°C) and 473 K (200°C), or with excess temperatures in the range 0-100 K the liquid stream penetrated the surface of the gauze-pack and boiling was contained within the gauzes (Fig 8). A quenched area surrounding the impact zone supplied liquid to the hot periphery by a wicking action, created by the capillary forces active within the matrix. With an initial gauze-pack temperature of 482 K, or an excess temperature of approximately 110 K, a short duration 'splash and spray' effect was observed (Fig 9), rapidly followed by quenching of the target zone.

When the gauze-pack initial temperature was between 473 and 573 K (*ie* with a temperature excess ΔT of 100-200 K), film-boiling effects became apparent. With the gauze-pack initially at temperatures greater than 590 K ($\Delta T > 220$ K), the impinging stream of fluid created a splash and spray containing small spheres of liquid (Fig 10). This was followed by the formation of a quenched zone and a quantity of liquid began to accumulate, attached to the lower surface of the gauze-pack (Fig 11). Small droplets of liquid emerged from the upper and lower surfaces of the matrix outside the quenched zone. From a comparative study of the films it could be seen that the width of the quenched zone decreased with increase of temperature (Fig 12). This, and the fact that the amount of liquid apparently rejected by the gauze above the target zone also increased with temperature, indicated that as the gauze-pack temperature of an EHT rose, one might expect a greater accumulation of liquid in the head-space. The fact that more liquid was observed to penetrate through

the gauzes as the initial temperature rose was not taken as necessarily indicating that the penetration depth into an EHT gauze-pack would increase, since the presence of further hot gauzes beneath the surface layers would affect the penetration. The duration of the initial splash and spray effects increased with rising start temperature, as did the average size of the droplets produced.

It was noted that, over the temperature range covered, the liquid stream was not rejected entirely by the gauze-pack; a quenched zone was produced, at the periphery of which film-boiling was seen to be active, evident from the presence of small liquid spheroids which did not wet the gauze filaments on impact, but deflected off the surface with no measurable change in size. Thus Leidenfrost film-boiling effects were observed and it was judged that these might be capable of playing a significant role in the operation of the prototype design of electrothermal hydrazine thruster.

It was decided that a more refined experiment should be designed, in order to give a more realistic representation of the prototype EHT and so that a greater range of gauze initial temperatures could be studied. In particular it was of interest to record and observe how the liquid droplets rejected from the gauze-pack behaved within the head-space, especially when subjected to interdroplet collisions and to impact with the head-space walls.

3.2 Series 2: partial simulation of prototype EHT

It can be seen from the schematic diagram (Fig 13) that the model used for the series 2 tests was more representative of the prototype thruster. The injector tube was identical in bore and external diameter to that used in the prototype. The head-space walls, while being open on two opposing faces to allow filming, were represented by plane surfaces. These were machined at the ends of the two heat sources which replaced the body of the thruster. The sources were heated electrically and were linked by a stainless steel plate which was used also to locate the injector. The gauze-pack, which incorporated thirty platinum gauzes, was identical in mesh and wire diameter to that used in the prototype EHTs (52 mesh \times 0.1 mm diameter wire) and was clamped to the two heat sources. The internal cross-section in the plane of view was approximately the same size as the prototype EHT design. Since the model was open, the build-up of pressure in the head-space was precluded.

By simulating the thruster walls and their attachment to the injector, this model could be used to simulate the vaporization phase of the first pulse of a train, where the injector/head-end joint would be at an elevated temperature, and where some degree of vaporization in the injector could occur.

The tests were performed with a similar photographic set-up as described for the series 1 tests (see Fig 8). The pulse durations filmed were again 100 ms, and the filming speed of 5000 frames/second, established as suitable for the first series, was maintained in order to resolve the transient events. An event mark and timing marks at 1 ms intervals were incorporated, appearing at the edge of the film.

A series of eight test runs was performed over a gauze-pack initial temperature range of 300-1000 K. Temperatures were measured by thermocouples spot-welded to the

platinum pack and to the heat sources in the positions shown (Fig 13). The steady-state volumetric flow rate through the injector was again 0.17 ml/s.

Some of the results, including frames extracted from the processed high-speed ciné film of the series 2 tests, are shown in Figs 14 to 24. For the purpose of the discussion, the effects are divided into four phenomena, which, while they may have overlapped chronologically on the filmed record, will be treated separately. The aspects are:

- (i) vaporization within the injector;
- (ii) formation of a quenched zone in the gauze-pack;
- (iii) growth of the quenched zone; and
- (iv) droplet collisions.

(i) Vaporization within the injector

During the lower temperature runs there was no evidence of vaporization within the injector; however, as the initial temperatures were raised the effects of vaporization in the injector became more pronounced. With a starting temperature (of the heat sources) of 504 K (or an excess temperature of 131 K), *ie* within the expected transition region (see Fig 5), a spray was visible from the tip of the injector for 1-2 ms (Fig 14). As the starting temperature was raised, the duration of the spray from the injector increased. The spray appeared to be composed of a mixture of vapour and atomised liquid. Collapse of the spray cone as the injector quenched was characterised as shown in Fig 15 by a central core of liquid impinging on the gauze-pack, the core being surrounded by a divergent stream of vapour. The change to this short-lived state will be termed the 'first flow transition'. Although the dynamic flow rate was not recorded (due to the unavailability of a flowmeter with suitable dynamic response), it was qualitatively apparent that the mass flow was inhibited during the vaporization phase. It may also be reasoned that boiling in the tube reduced the mass flow rate, since there would have been a local pressure increase resulting in a reduction of pressure gradient within the liquid. Total quenching of the injector followed, with the apparent establishment of full flow and the time at which this was determined to have occurred will be termed the 'second flow transition'. The duration of the vaporization/atomisation within the injector, *ie* the time to the second flow transition, increased as the initial body temperature was raised. This duration of vaporization/atomisation has been plotted in Fig 16. It can be seen that the two flow transitions described above became more defined at higher initial temperatures, as the time to the first flow transition and the time between the two flow conditions both increased with temperature. If the different latent heats of vaporization of water and hydrazine are considered it may be expected that the vaporization times would be greater for hydrazine, even in the absence of any decomposition.

(ii) Formation of a quenched zone

For gauze-pack initial excess temperatures below 120 K the behaviour was much the same as that described by the series 1 test results: the impinging liquid stream rapidly quenched the gauzes at the target zone, to a temperature below the boiling point of the liquid, and the stream was taken up rapidly by the gauze-pack without splashback (see Fig 17). The liquid was then wicked towards the periphery where, for heat source

temperatures of 373-493 K ($\Delta T = 0-120$ K), nucleate-boiling was observed at the heat source wall.

As the initial excess temperature, ΔT , was raised above 120 K, the collapse of the partially vaporized spray (described above) as the injector quenched, was followed or at higher temperatures accompanied by some splashback from the gauze-pack surface (Fig 18). At the higher end of the explored temperature range, some coalescence of the mist into droplets occurred on impact with the surface of the gauze-pack even before the first transition of injector flow had occurred (Fig 19). The droplets formed did not wet the surface of the pack. After the second injector flow transition (and sometimes between the two transitions, which were described earlier), a definite quenched zone appeared at the impact area. The size of this zone at the surface of the pack, and its variation with elapsed time could be observed from the film because of the emission of small globules of liquid, from its periphery, into the head-space. This has not been illustrated here as it cannot be shown adequately in a still photograph.

(iii) Growth of the quenched zone

Initial growth of the quenched zone was beneath the surface of the gauze-pack, adjacent to the target area. This was followed by the build-up of a liquid blob on the surface of the pack (Fig 20). The reason for this partial rejection from the gauze-pack was considered to be due to the overcoming of the capillary forces, by the local pressure of steam generated by film-boiling (or mixed film- and nucleate-boiling) within the interstices of the gauze matrix. The liquid-quenched zone expanded until the thermal gradient, across the gauze matrix between heat sources and liquid, was such that film-boiling would occur (providing the heat-source temperature remained sufficiently high). Thus, with a quenched zone within the pack growing very slowly (relatively) and vaporization inhibited by film-boiling, as the inlet flow continued the liquid blob grew out from the surface of the pack (Fig 21), sometimes rotating or oscillating about the impinging jet of liquid. The free droplets in the head-space in Figs 20 and 21 were emitted from the non-quenched surface of the gauze-pack.

The width of the quenched zone increased with time until it filled the surface of the gauze-pack. As the liquid reached the edges of the pack (Fig 22) it was repelled by the heat-source walls in typical film-boiling style, and large globules of liquid were often ejected into the head-space from the periphery of the pack.

(iv) Droplet collisions

It has been indicated above that there were three sources of free droplets in the head-space: those generated by the coalescence of mist above the gauze-pack; those generated by film-boiling effects within the gauze-pack and which emerged into the head-space from the non-quenched area of the gauze-pack surface; and those which were created as the quenched zone spread to, and was rejected by, the body walls. Once generated, all these droplets were subject to random collisions with the head-space walls, other droplets, the liquid stream, the quenched zone, or the non-quenched gauze surface.

It was noted that the Leidenfrost point for the head-space walls was in the region of $\Delta T = 120$ K, i.e. $T = 490$ K. At temperatures below this value those few droplets that

were observed vaporized rapidly by nucleate-boiling when in contact with the head-space walls. At higher temperatures, the droplets failed to wet the surface on collision with the walls, and the heat transfer to the droplets was minimal. This was demonstrated by the fact that the majority of droplets rebounded from the head-space walls with no measurable decrease in apparent size and usually with little variation in speed. These droplets were in effect subject to elastic collisions with the walls.

The presence of larger droplets in the head-space as the initial temperatures were increased was accounted for partly by the rejection of large droplets from the target zone of the gauze-pack (Fig 23), but it was also affected by the quantity of smaller droplets present. That is, the greater the number of small droplets, the higher the probability of interdroplet collisions leading to amalgamation into larger droplets.

Collision of a droplet with the established liquid stream emerging from the injector usually resulted in the droplet being entrained by the stream due to surface tension effects. It was possible, however, if it had sufficient momentum, for a droplet to cause a temporary disruption of the stream. Fig 24 illustrates both these effects. A droplet is being entrained by a fluid stream previously disrupted by collision of another droplet.

Droplets in collision with the quenched zone were taken up by the zone. As the quenched zone spread with time across the surface of the gauze-pack there was an increasing probability of these collisions occurring, and thus a tendency for all the non-vaporized liquid to accumulate at the quenched zone. Collisions of droplets with the non-quenched surface of the gauze, *ie* at a temperature greater than the local Leidenfrost point, were subject to film-boiling and were therefore rejected from the pack.

4 DISCUSSION OF RESULTS

The tests and the results described yielded a much greater understanding of the physical processes involved in propellant injection and vaporization in the prototype EHT configuration.

(i) Using water, film-boiling effects were observed with the head-space wall temperature as low as 490 K (*ie* with an excess temperature, ΔT , of about 120 K). They became significant at a temperature in excess of 520 K ($\Delta T > 150$ K) and became increasingly pronounced as the initial temperature was raised further. Thus the Leidenfrost effect was seen to play an important role in inhibiting the vaporization of propellant within the thruster body.

(ii) The duration of splashback from the gauze-pack surface increased with initial temperature, demonstrating again the effects of film-boiling, which was by definition maintained until the local gauze temperature was below the Leidenfrost point. Nowhere in the range of temperatures explored however was the liquid stream totally rejected by the gauze-pack surface; a quenched zone was always formed.

(iii) Depth of penetration of the gauze-pack decreased with increasing gauze-pack temperature, associated with a greater build-up of liquid in the head-space and delayed lateral penetration within the matrix.

(iv) Vaporization within the injector also appeared to play a significant role, by reducing the initial mass flow into the thrust chamber. The duration of this vaporization/atomisation increased with temperature. It was thought that film-boiling, possibly aided by a change to turbulent flow, provided the mechanism by which the water was atomised within the injector. Although this inhibited the mass flow during the period over which it occurred, the suggestion was made that if the injector could be made to operate continuously in this mode at an increased mass flow rate, it would provide a novel means of achieving atomisation. However, the suggestion was discarded in connection with the prototype EHT due to the wide range of flow rate over which the thruster was expected to operate in the blow-down mode, combined with the complexities involved in designing the device to operate at various duty cycles from the pulsed mode to steady-state operation.

5 PROPOSALS FOR FURTHER WORK

On completion of the flow visualization studies which have been described, it was clear that further research would be required.

(i) In order to ensure that the vaporization effects were valid in the presence of thermally decomposing hydrazine vapour, the flow visualization studies should be extended to incorporate the exothermal decomposition phase. This would involve the design and manufacture of a suitable see-through electrothermal hydrazine thruster, whose internal performance would closely resemble that of the prototype EHT;

(ii) Assuming the validity of the flow visualization studies already performed using water, alternative thruster configurations should be identified and the high-speed cinematographic studies should be extended to their transient vaporization behaviour;

(iii) Means of active or passive cooling of the injector should be explored to investigate the effect of injector temperatures on thruster response.

At the time of writing research has been continued in the directions indicated, and the results, which are extremely promising, will be the subjects of further reports. In particular some high-speed cinematographic results obtained with hydrazine have been presented briefly in Ref 20.

6 CONCLUSIONS

Certain anomalous behaviour of a prototype electrothermal hydrazine thruster has been described.

Some high-speed cinematographic studies were made of transient vaporization phenomena using water within a model of the EHT.

The conclusion was drawn that film-boiling effects similar to those described by the Leidenfrost phenomenon were likely to occur within the decomposition chamber of the prototype EHT, and these were likely to result in inhibition of vaporization and affect the decomposition rate of the propellant.

It was also indicated that complete, or even partial, vaporization of the propellant within the injector could have a deleterious effect on the starting transient of the prototype thruster.

A need for further experimental work was identified.

Acknowledgment

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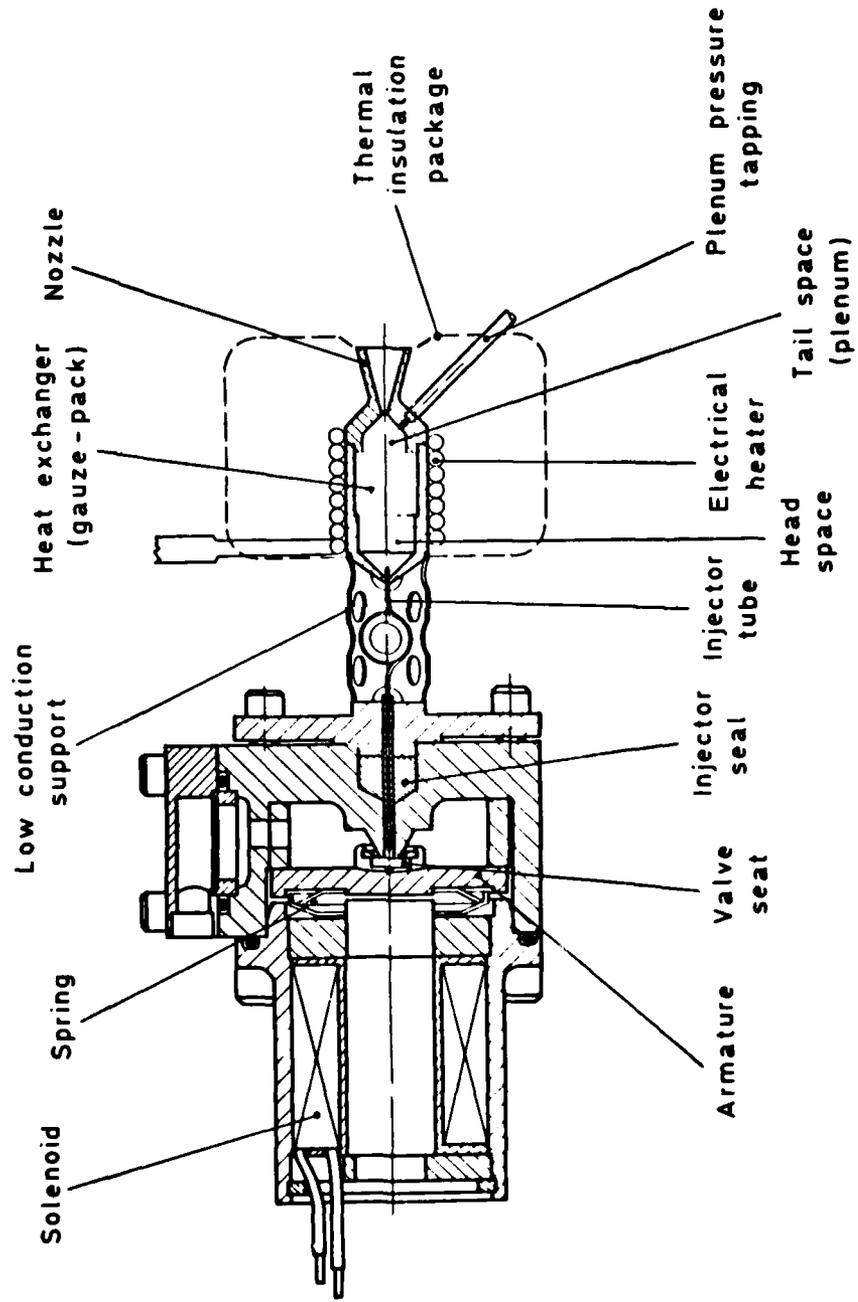


Fig 1

Fig 1 RAE prototype EHT design (EF1) coupled to RAE fast response flow control valve

Figs 2&3

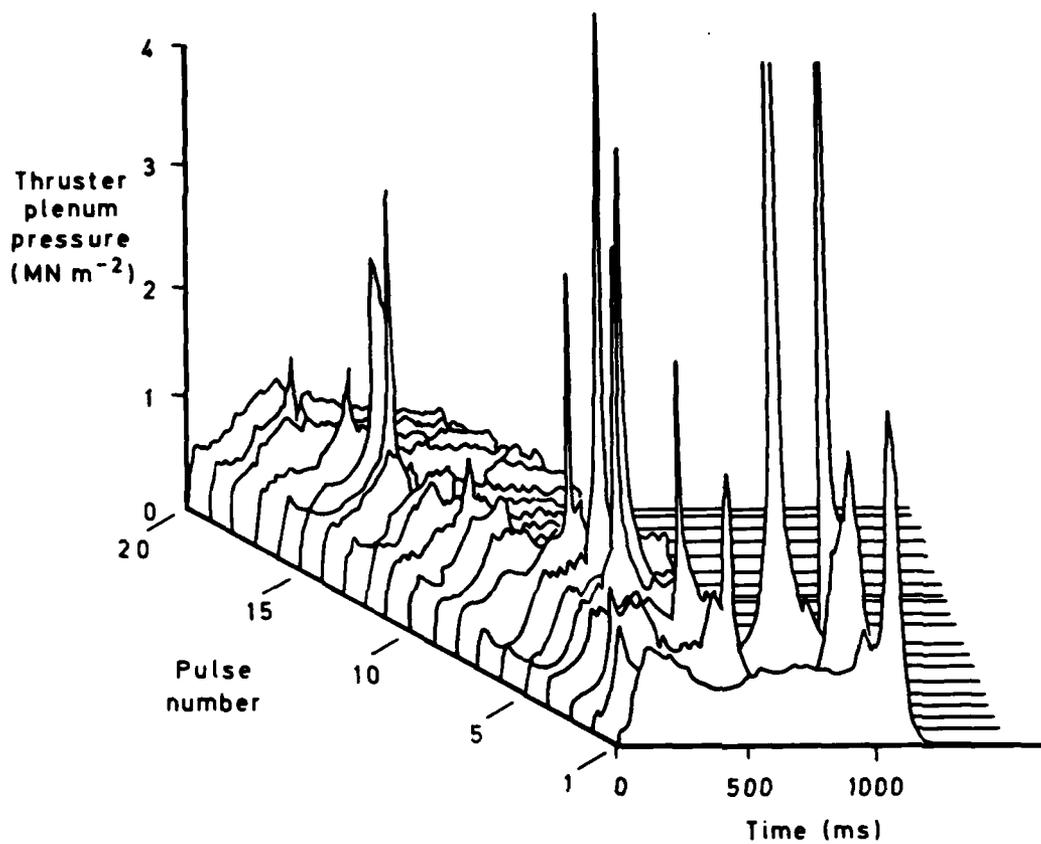


Fig 2 Typical train of pulses, obtained with prototype thruster EF1/4. (Fuel supply pressure 1.8 MN m^{-2} . Initial holding temperature 740 K . Duty cycle 20%)

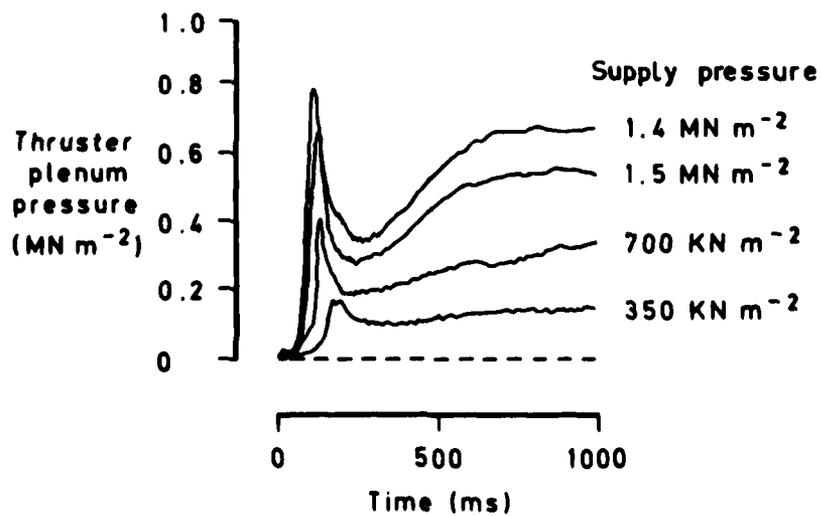


Fig 3 Effect of fuel supply pressure on starting characteristic of prototype thruster EF1/3. (Initial holding temperature constant at 750 K)

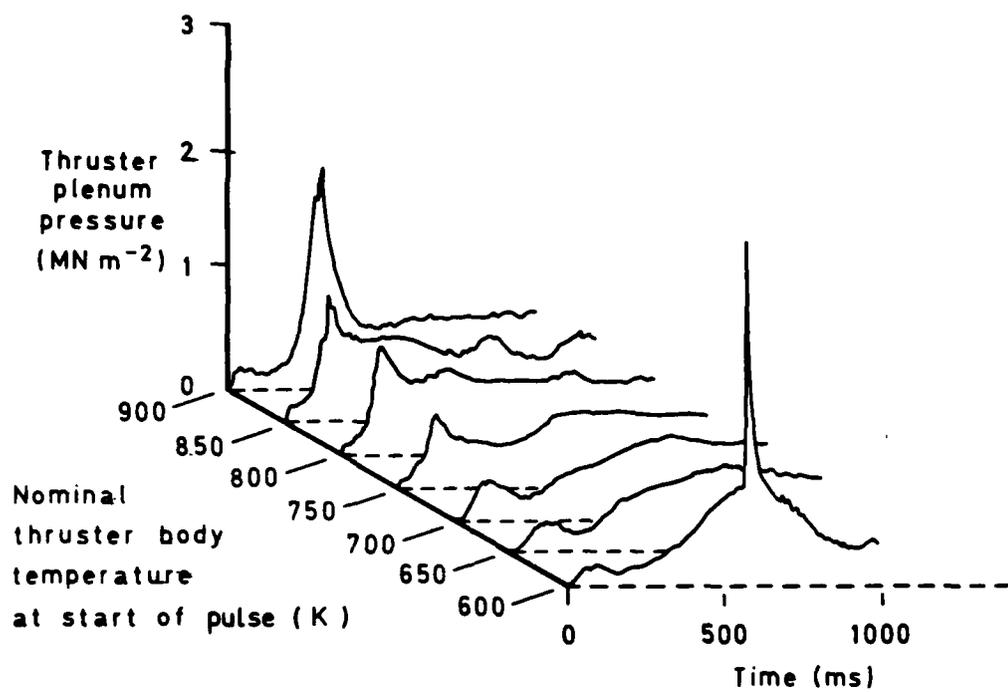


Fig 4 Effect of initial holding temperature on starting characteristic of prototype thruster EF1/4. (Fuel supply pressure constant at 1.4 MN m⁻²)

Fig 5

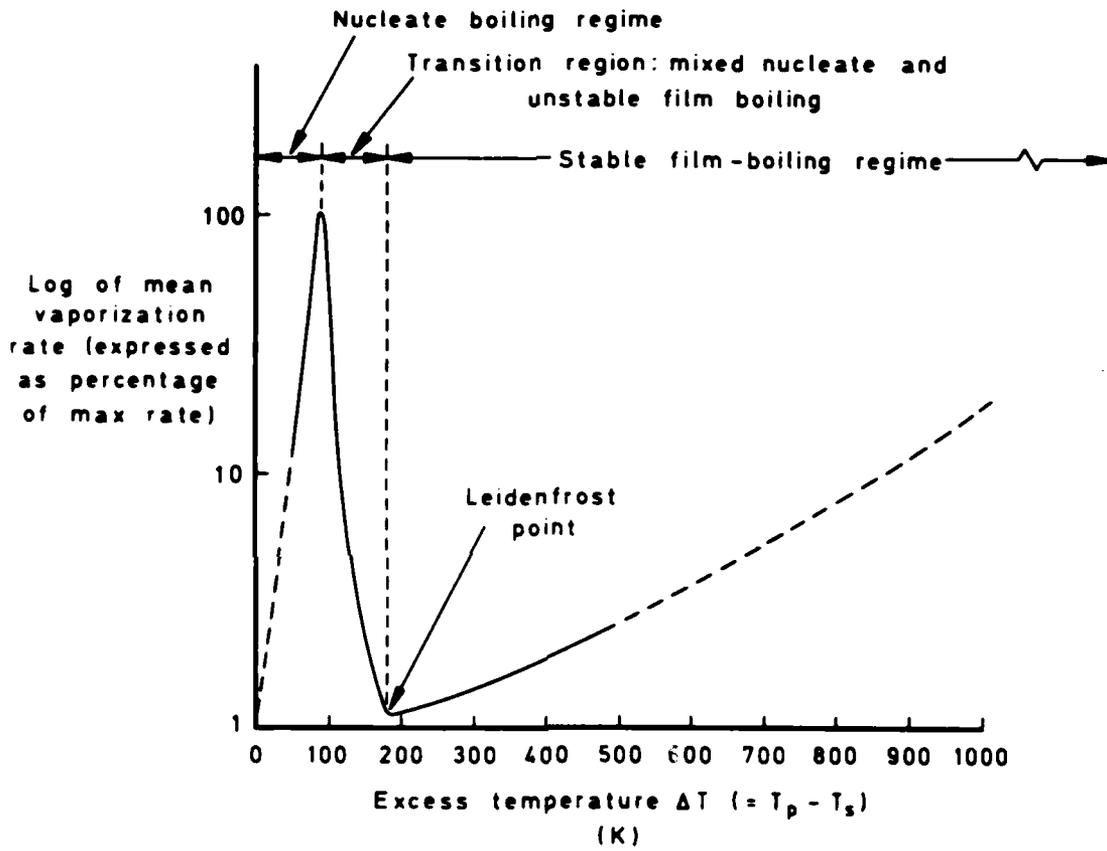


Fig 5 Typical vaporization rate for initially uniform water droplets placed on a plane heated surface

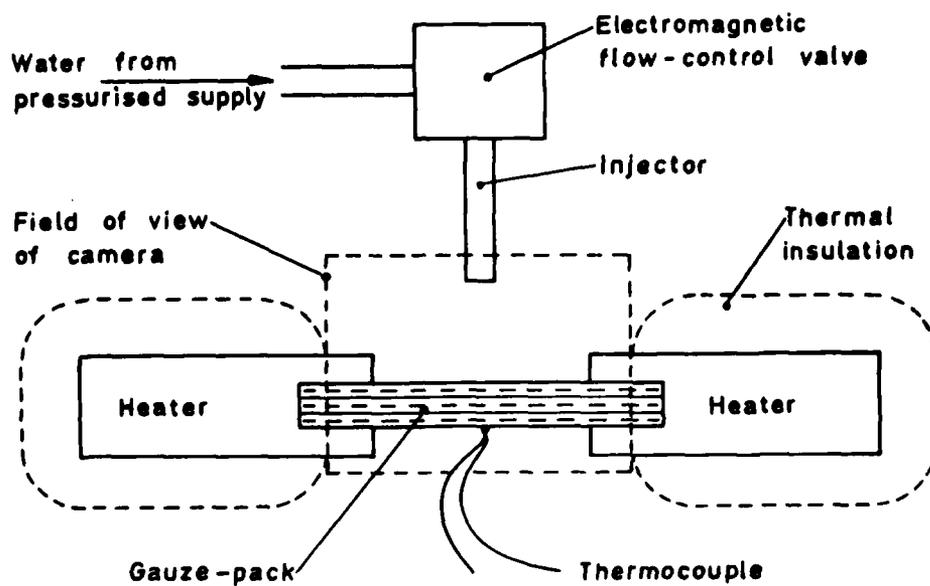


Fig 6 Schematic diagram of Series 1 apparatus

Fig 7

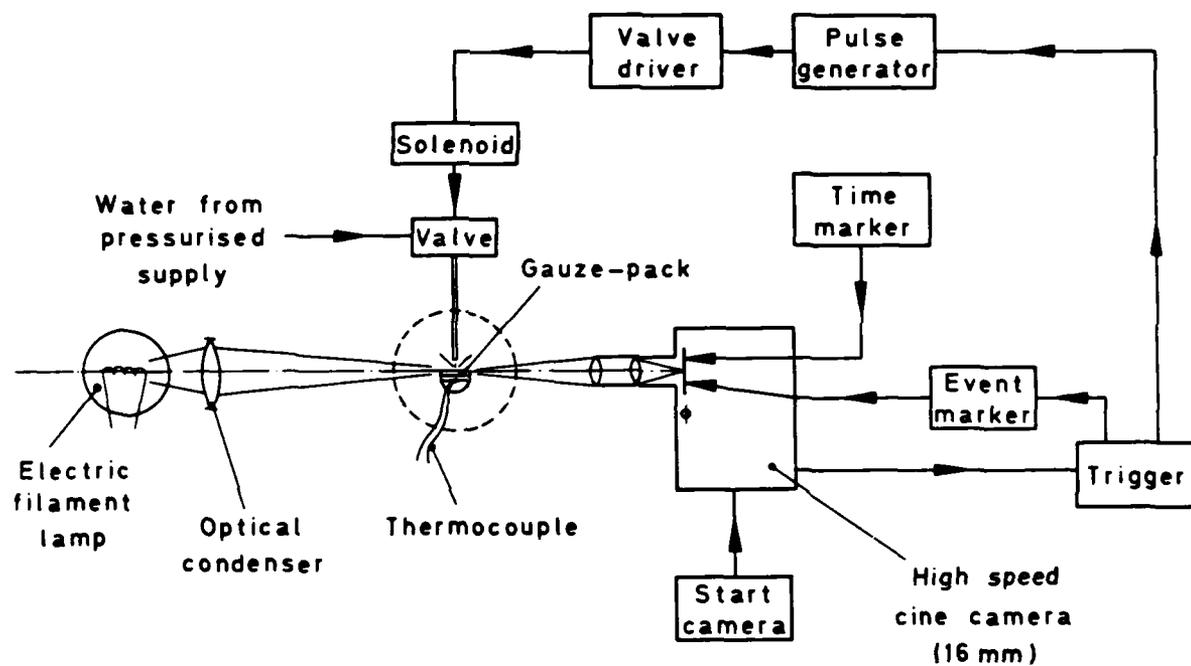
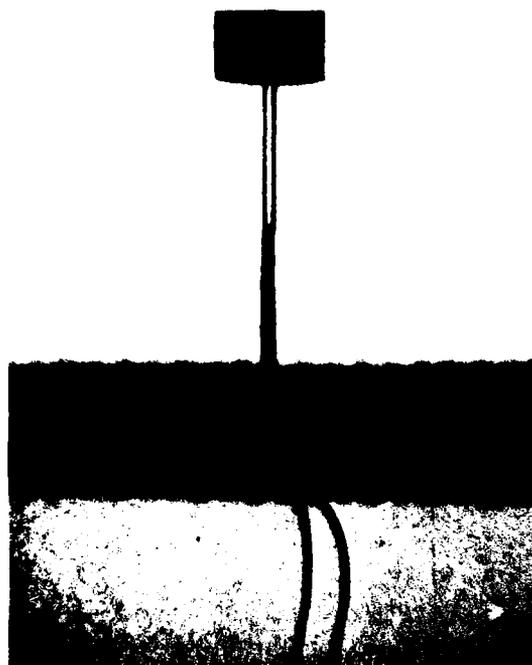
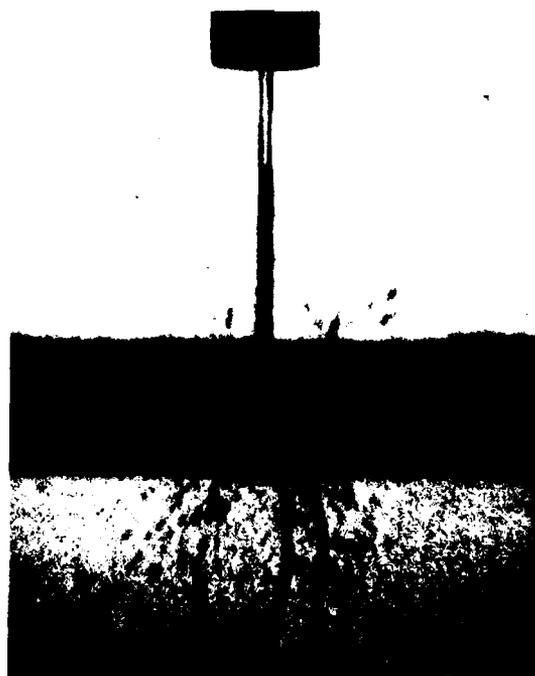


Fig 7 Flow visualization experiment, schematic (Series 1 depicted)



Initial gauze temperature = 406 K ($\Delta T = 33$ K)
Time: 1.0 ms

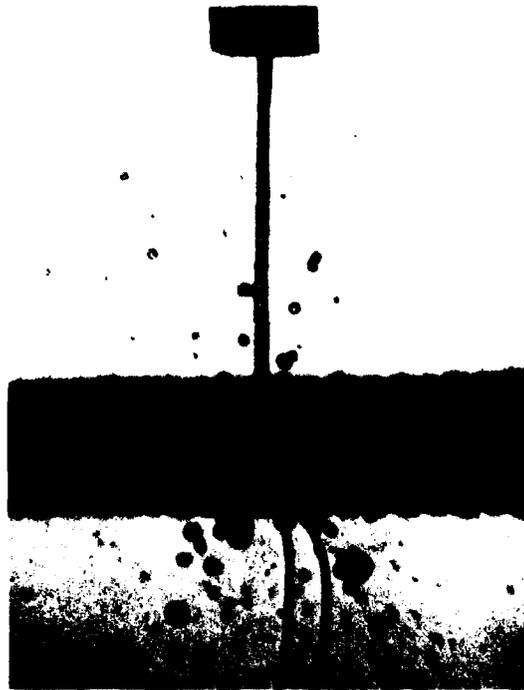
Fig 8 Gauze-pack penetration



Initial gauze temperature = 482 K ($\Delta T = 109$ K)
Time 1.0 ms

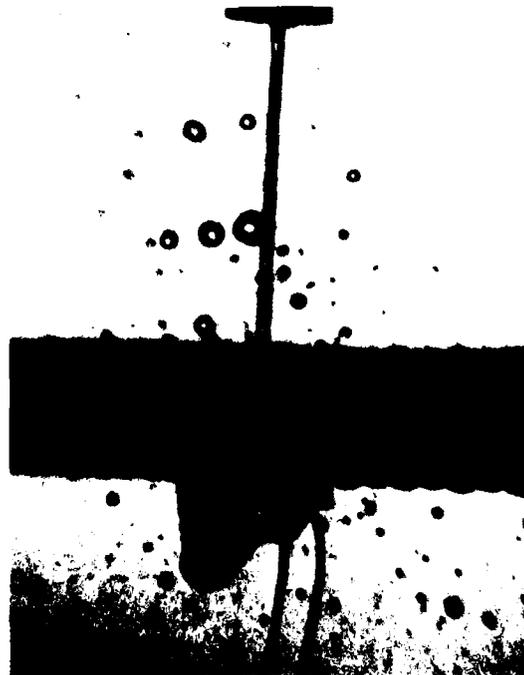
Fig 9 'Splash-and-spray' effect

Figs 10&11



Initial gauze temperature = 594 K ($\Delta T = 221$ K)
Time: 5 ms

Fig 10 Evidence of film-boiling within gauze-pack



Initial gauze temperature = 594 K ($\Delta T = 221$ K)
Time: 21 ms

Fig 11 Quenched zone build-up

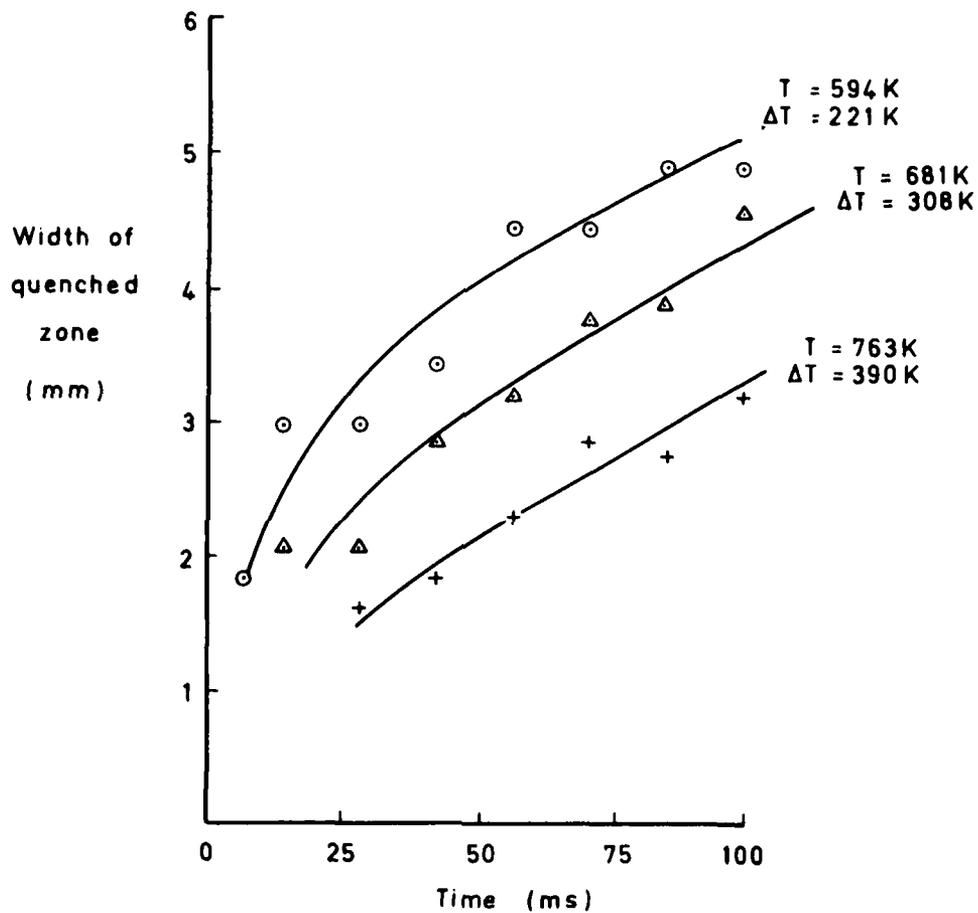


Fig 12 Variation of width of quenched zone with time and temperature

Fig 13

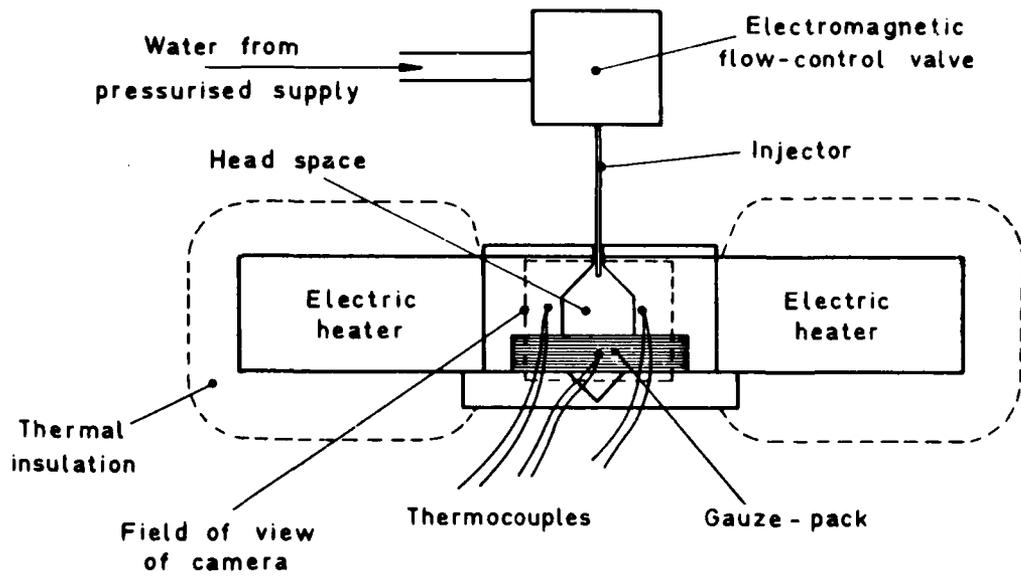
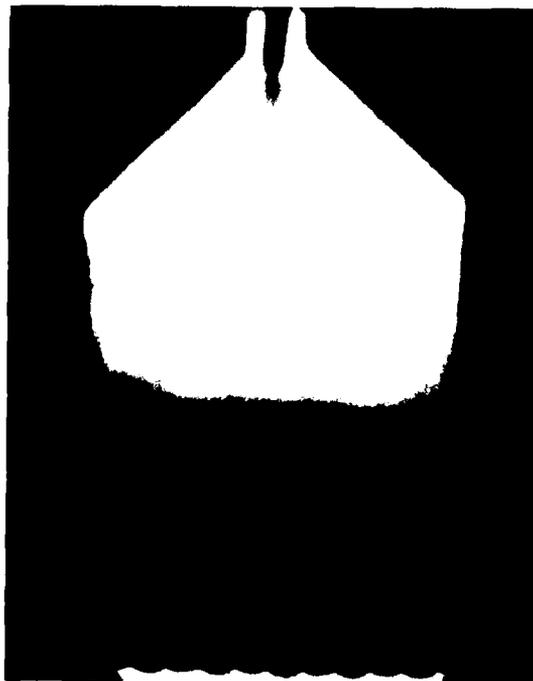
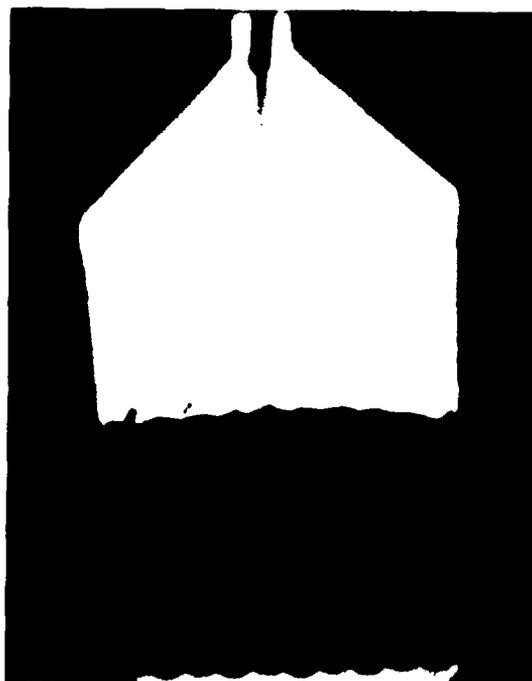


Fig 13 Schematic diagram of Series 2 apparatus



Initial body temperature = 504 K ($\Delta T = 131$ K)
Time: 1 ms

Fig 14 Initial vaporization in injector



Initial body temperature 833 K ($\Delta T = 460$ K)
Time: 18 ms

Fig 15 First flow transition

Fig 16

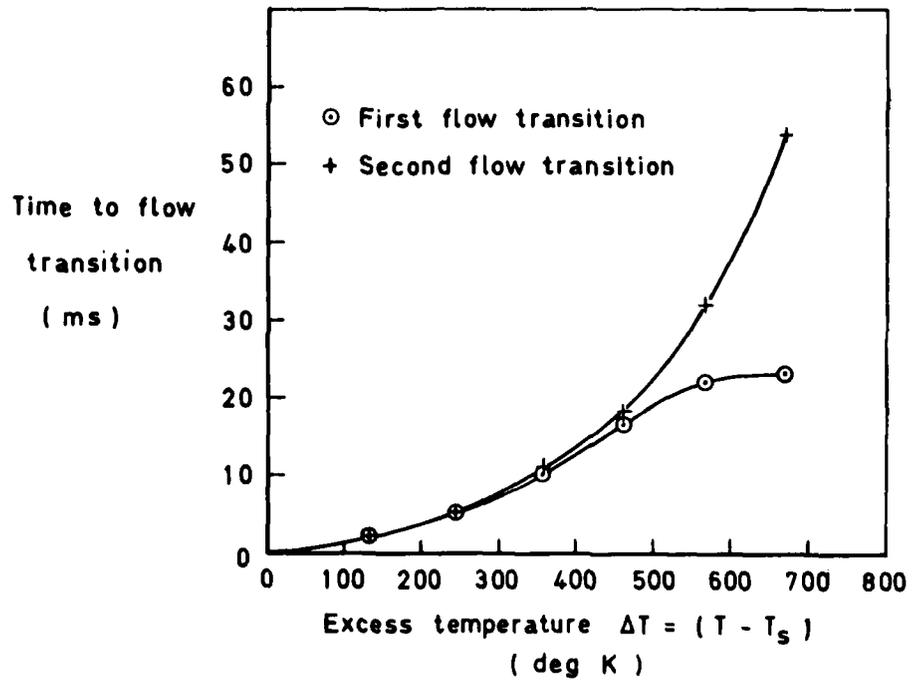
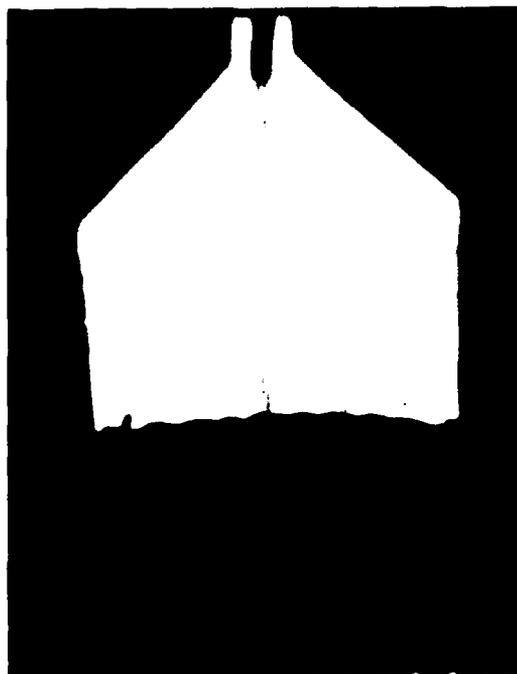


Fig 16 Injector quenching characteristics for Series 2 tests



Initial temperature $< \sim 390$ K
 $\Delta T < 120$ K

Fig 17 'No splashback' condition at low initial temperature



Initial gauze-pack temperature 998 K
 $\Delta T = 625$ K (time = 27 ms)

Fig 18 Splashback from gauze-pack at first flow transition

Figs 19&20



Initial gauze-pack temperature 998 K
 $\Delta T = 625$ K (time = 15 ms)

Fig 19 Coalescence of propellant mist into droplets on impact with gauze-pack prior to first flow transition



Initial gauze-pack temperature 698 K
 $\Delta T = 325$ K (time = 15 ms)

Fig 20 Build-up of liquid blob attached to quenched zone



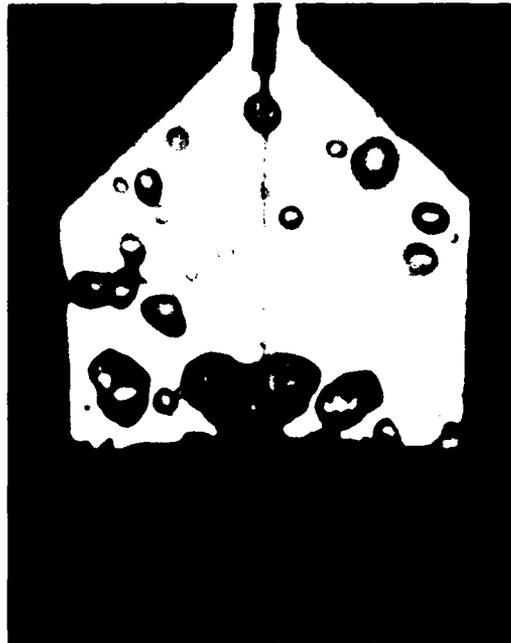
Initial gauze-pack temperature 698 K
 $\Delta T = 325$ K (time = 22 ms)

Fig 21 Growth of liquid blob



Initial gauze-pack temperature 897 K
 $\Delta T = 524$ K (time = 95 ms)

Fig 22 Wave motion in liquid blob as quenched zone approaches head space walls



Initial gauze-pack temperature 998 K
 $\Delta T = 625$ K (time = 50 ms)

Fig 23 Rejection of large droplets into head space



Initial gauze-pack temperature 897 K
 $\Delta T = 524$ K (time = 72 ms)

Fig 24 Entrainment of droplet into fluid stream

REPORT DOCUMENTATION PAGE

Overall security classification of this page

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17. Abstract Tests of prototype electrothermal hydrazine thrusters (EHTs), intended for satellite attitude and orbit control, revealed anomalies in performance, attributed to problems in vaporization. The process of vaporization was studied by high-speed cinematography, with water substituted for hydrazine in models of the EHT. The results of the flow visualization research are described, and it is concluded that Leidenfrost film-boiling effects inhibited vaporization and affected the performance of the thrusters.			

10/11

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