Engineering Notes

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Propellant Flow Rate through Simulated Liquid-Core Nuclear Rocket Fuel Bed

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ONE of the concepts proposed for utilizing nuclear energy for rocket propulsion is that in which fissioning uranium fuel is maintained in a molten liquid state. It was predicted[1–3] that bubbling propellant gas through a liquid nuclear fuel bed would raise the plenum-chamber temperature of the rocket above 4000°K, and would result in a specific impulse of up to 1500 sec. The proposed liquid-core nuclear rocket would consist of one large rotating cylinder[2] or a bundle of small rotating cylinders[3] containing molten nuclear fuel. The chamber walls would be porous, and the centrifugal force of rotation would cause the liquid fuel to form a uniformly thick layer on the walls. The cold hydrogen propellant gas would then be injected radially inward through the porous walls. The hydrogen gas bubbling through the liquid would be heated by the hot molten uranium compound, and the fission energy would thus be transferred to the propellant gas. The hot hydrogen would be expelled from the rocket chamber through a hole on the cylinder axis to provide the rocket thrust.

Earlier studies[1–3] indicate that the heat-transfer rate from liquid fuel to gas bubbles would be sufficiently large and that the rate of loss of fuel material through vaporization could be kept sufficiently small to make the liquid-core concept feasible. However, these studies did not estimate the rotational speed of the fuel chamber necessary for the passage of the required propellant flow. These effects were not included because the studies concentrated on the dynamics of individual bubbles rather than the evaluation of over all characteristics of two-phase flow.

Shortly after the publication of Refs. 2 and 3, Zuber and Finlay[4] reported a comprehensive study on the characteristics of two-phase flows. From a dimensional analysis and the experimental data taken in a flow through pipes, the gas flow-rate formula was derived as

$$Q = 1.53\, A\, (\sigma a/\rho_l)^{0.25} X/(1 - CX) \qquad (1)$$

where Q = total gas flow rate, cc/sec, σ = surface tension, dyne/cm, ρ_l = liquid density, g/cm³, A = total surface area of liquid bed, cm², a = centrifugal acceleration, cm/sec², X = void fraction, dimensionless, C = empirical constant, $1.1 < C < 1.6$. According to Eq. (1), an extremely large rpm would be necessary in order to pass the propellant flow rate envisioned in Ref. 3. In view of the seriousness of the consequences, it was felt necessary to first test the validity of Eq. (1) for the pertinent flow configuration, i.e., a two-phase flow in a rotating cylinder under high-centrifugal acceleration. The work described in the present Note was initiated for this purpose.

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To partially simulate a rotating liquid-core nuclear rocket chamber, a model was built as shown in Fig. 1. The chamber is 19 cm in diameter and 14 cm long, and is constructed of perforated nickel sheet 0.3-mm thick with 140 holes/cm². The holes are 0.076 mm in diameter and the total flow area of the chamber wall (i.e., the total area of the holes) is approximately 0.6% of the total area of the cylindrical surface. The cylinder rotates on a hollow shaft at either approximately 390 or 850 rpm, producing tangential velocities of about 3.9 or 8.5 m/sec, corresponding to centrifugal accelerations of 15.8g and 77g, respectively. Water, simulating the liquid uranium fuel, forms a uniformly thick layer on the chamber wall due to the centrifugal acceleration. The vessel containing the rotating cylinder is pressurized with prefiltered compressed air that simulates the hydrogen propellant. The pressure forces the air to be injected through the porous chamber walls and to bubble through the water. The air then exhausts to the atmosphere through the hollow drive shaft.

Motion pictures and visual observations of the rotating chamber under a stroboscope show that a steady-state, two-phase flow is established immediately as the rotation commences. Air and water appear to be generally well separated, the air passing through the liquid as tiny bubbles of the order of 0.1-cm diam. At low airflow rates, the two-phase flow developed in the chamber is laminar and highly stable. However, at such low airflow rates, the distribution of bubbles is concentrated in a highly nonuniform manner; i.e., the air flows through only a small portion of the available porous wall surface, and for most of the porous wall areas, the airflow seems to be blocked. At high airflow rates, the blocking

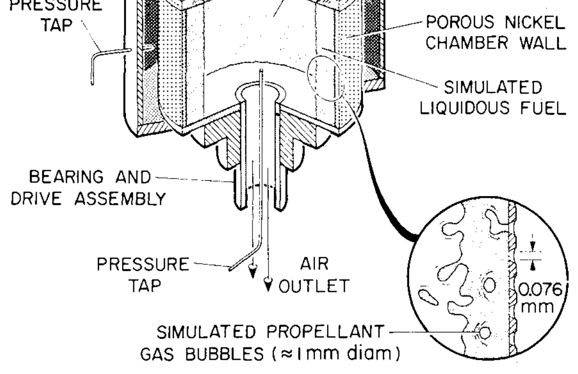

Fig. 1 Schematic of simulated rocket chamber in operation.

phenomenon is greatly reduced but the two-phase flow becomes irregular and unstable. At the highest airflow, a violent bulk motion of the water was observed accompanied by the coalescence and breakup of bubbles. Such a regime would not be acceptable in a real rocket and thus a practical limit on the maximum airflow rate is imposed. There was no sign of secondary flows, i.e., the airflow moved only in the direction normal to the main rotation, as observed from the motions of bubbles. The water layer thickness was determined visually using a scale, observed under the stroboscope, etched on the Plexiglas lid of the rotating cylinder chamber.

The stability of the flow is manifested by the flow rate (Q) vs driving pressure (Δp) plot shown in Fig. 2. The data in Fig. 2 were taken in the intermediate flow regime where neither the blocking nor the coalescence of bubbles occurred. The finite positive slope in the Q-Δp plot, $dQ/d(\Delta p) > 0$, signifies that the air-flow rate can be controlled stably by setting the driving pressure to the desired value. The observed Q-Δp relationship can be explained quantitatively, but the explanation is omitted here since it is irrelevant to the main theme of the present Note.

To verify the validity of Eq. (1), it is necessary to measure the void fraction X at an arbitrary flow rate Q. In the present test, the void fraction was determined from the thickness of the water layer. The thickness of water layer was measured first with a negligibly small airflow rate; then, with a large airflow rate through the system, the thickness was measured again. The difference in the water layer thicknesses was attributed to the void fraction, the loss of water during the time period between the two measurements being neglected.

To confirm that a negligible amount of water is lost during the approximately 1 min period needed for the void fraction measurement, a separate measurement of water loss rate was conducted. The variation in the water layer thickness was observed over time periods extending up to 90 min under several different operating conditions. The result of these tests showed that the loss of water occurs mainly within the first 20 min after the commencement of chamber rotation. The loss rate becomes less than 1% (of contained water) per minute after this 20 min transient period. The void fraction measurements were made after the transient phenomenon has elapsed.

With this assurance, the void fraction was determined for the airflow rate range between 6000 and 9000 std cc/sec. The result showed the void fraction to be approximately 0.11 ± 0.025 for all cases. The relatively large error limits result from the fact that the surface of the water layer could not be determined clearly because of turbulent surface motion. The uncertainty in the water layer thickness was the reason also for not conducting the void fraction measurement at flow rates below 6000 cc/sec. Figure 3 compares the observed flow rate with Eq. (1). As shown in the figure, the experimental results agree with the formula to within the accuracy of measurement. Thus Eq. (1), which was derived from tests in a 1-g environment in pipes, is seen to be valid also for a high-g environment in the rotating chamber tested here.

The significance of Eq. (1) is illustrated in the following sample calculation. In Ref. 3, a calculation was made for a reference prototype rocket engine which weighed 3620 kg and delivered 4410 kg of thrust with a specific impulse of 1500 sec, the required propellant flow rate being 2.94 kg/sec. At the maximum possible void fraction of 0.3 assumed in Ref. 3, the centrifugal acceleration needed to pass a flow rate of 2.94 kg/sec is calculated from Eq. (1) to be as shown in Table 1. These accelerations and pressures impose quite stringent requirements on the confining structure.

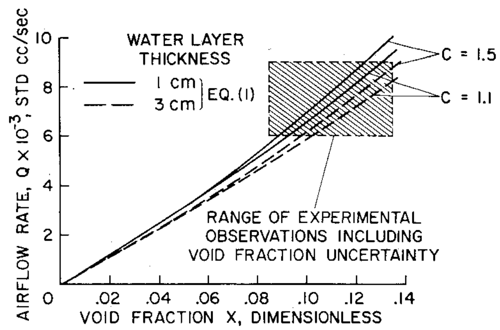

Fig. 3 Comparison between theory and measurement on airflow rate.

Table 1 Calculations of prototype rocket engine

Chamber pressure	Centrifugal acceleration
10 atm	1.4×10^5 g
30 atm	1700 g
100 atm	14 g

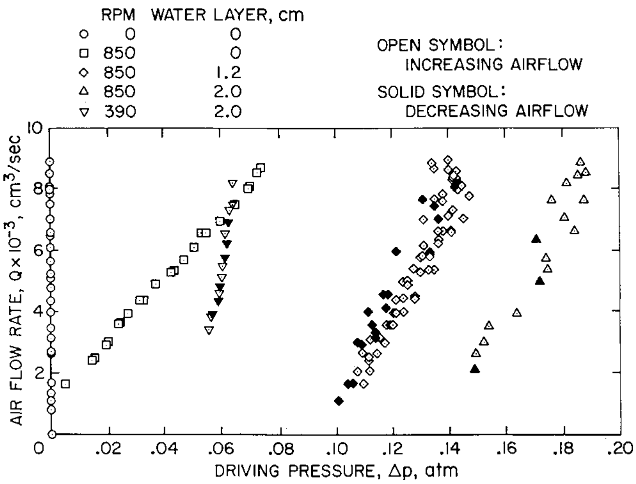

Fig. 2 Airflow rate through chamber.

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