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DC Power Control for a Liquid-Fed Resistojet

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DC POWER CONTROL FOR A LIQUID-FED RESISTOJET

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ABSTRACT

A simple breadboard power controller was designed and demonstrated for a new liquid-fed water resistojet. The one piece laboratory model thruster has an integrated vaporizer/superheater using a single heating element. Heater temperature was maintained at or near a preset reference value with the closed loop controller providing pulse width modulated (PWM) dc power into the thruster heater. A combined thruster, temperature readout, PWM transfer function was experimentally determined. This transfer function was used to design a proportional plus integral controller that demonstrated zero steady state error, conservative stability margins and adequate transient response to step changes in propellant flow rate, input voltage and temperature reference. Initial turn on temperature overshoot from room temperature to a 650 °C setpoint was 80 °C. In addition, EMI was alleviated by reducing heater dI/dt and dV/dt using a simple diode-inductor-capacitor network. Based on limited initial tests, thruster preheat with no propellant flow was necessary to achieve stable system operation during startup. Breadboard power efficiency was 99 percent at 1 kW, and component mass was 0.4 kg excluding the power loss and mass of an input filter required for spacecraft integration.

NOMENCLATURE

$G(s)$	open loop thruster and power controller system transfer function
$G_a(s)$	combined PWM power circuit, thruster and temperature readout transfer function
$G_c(s)$	proportional plus integral controller transfer function
$G_p(s)$	PWM power circuit transfer function, W/V
$G_R(s)$	temperature readout transfer function, V/°C
$G_T(s)$	thruster transfer function, °C/W
I	thruster current, A
R	thruster heater resistance,
s	Laplace transform variable
t	time, sec
T_d	transportation lag, sec
v_M	small signal sinusoidal power control signal, V
v_T	small signal sinusoidal voltage proportional to temperature, V
V	thruster voltage, V
V_{in}	dc input voltage from bus, V
ϕ	phase difference between v_M and v_T, deg
ω	frequency of v_M and v_T, rad/sec

INTRODUCTION

Multipropellant resistojets, for which water is a candidate propellant, have been baselined as the low-thrust propulsion system option for space stations.[1] Water resistojets have also been baselined for orbit maintenance duty on the man-tended Industrial Space Facility scheduled for launch in the early 1990's.[2]

The use of water as a resistojet propellant for manned or man-tended platforms has a number of attractive features. Scavenged waste water which might otherwise have to be returned to Earth could be used to provide impulse for drag make-up or orbit control. Space systems operating on water economies could easily store liquid water in small, low-pressure tanks, electrolyze this water for use in hydrogen/oxygen rockets to perform high-thrust propulsion tasks, and use water from the same storage tanks to feed water resistojets for low-thrust propulsion. Furthermore, the benign chemistry of water and steam makes it well-suited to manned systems, where toxicity and contamination are important.

Water was one of the candidate propellants for a biowaste resistojet system investigated as part of the Manned Orbital Research Laboratory (MORL) program conducted during the early 1970's. Preliminary evaluation of basic components including the thruster, steam generator, compressors, and pumps was undertaken.[3,4] The MORL program and the associated biowaste resistojet technology work was terminated in the early 1970's.

Recently, it was determined that a conceptually simple, integrated water vaporizer/superheater could be built that would serve as a one piece thruster with a single heater. A second generation laboratory model (Figs. 1 and 2) of this thruster concept was designed, constructed and is being tested to investigate its functional characteristics.[5]

The work described here is an initial experimental investigation of closed loop control for the liquid-fed water resistojet. As part of this effort, a simple, high efficiency, low mass, compensated control loop breadboard power controller was developed. The controller senses heater temperature and provides pulse width modulated (PWM) dc power to the thruster to maintain that temperature at or near some preset reference value. This approach was chosen for its simplicity and ability to ensure long thruster heater life. A combined thruster, PWM power circuit, and temperature sensor small signal transfer function was experimentally determined. Based on that transfer function, a compensated control loop was designed to provide conservative stability margins, and adequate steady state error and transient response. Thruster and power controller steady state and transient data are presented for initial startup, and for step changes in propellant flow rate, temperature setpoint and input voltage.

REQUIREMENTS

Spacecraft Considerations

The thruster system must be compatible with a single point power ground system. The power return must be isolated from spacecraft structure. For the type controller presented here, the issue of whether the spacecraft battery or power system can tolerate pulsed loading should be decided before the selection of controller operating frequency.

Thruster System Considerations

The thruster system must provide either fixed or variable values of specific impulse and/or thrust levels. Heater temperature, power, and propellant flow rates need to be controlled or adjusted, within limits, to achieve the necessary steady state performance. Additionally, for functions such as attitude control, thruster operation may require duty ratio control (off pulsing). Based on the foregoing, a wide variety of candidate control schemes could have been implemented. For this initial effort, heater temperature was chosen to be maintained at or near a variable reference value by automatic closed loop adjustment of power independent of propellant flow rate. This ensures long heater life and results in a simple controller. If desired, the reference temperature could be set as a function of flow rate. In this way, steady state power demand could be established which was not set by a reference power. Alternatively, the reference temperature could be changed by ground or external command.

The controller temperature sensor was placed at the inlet of the superheater (Fig. 1). This location was previously found to be most sensitive to steam quality (droplet content) and flow rate.

The thruster heater (Fig. 1) comprises a nichrome element, MgO insulator and Inconel sheath. The heater element is electrically isolated at the thruster from structure ground so transformer isolation is not necessary. Furthermore, the thruster heater resistance can be designed to match any power bus voltage. In addition, the nichrome element has a low temperature coefficient of resistance, so there is no need to provide cold start surge current limiting. These thruster heater characteristics allow a simple PWM power control technique to be used.

DESIGN

Design Philosophy

The design objective was to demonstrate a control and power electronics concept for the liquid-fed water resistojet. Of paramount importance to the propulsion systems for space stations and the mantended Industrial Space Facility, are long life, low maintenance, and simplicity. High power efficiency is also especially desirable for the Industrial Space Facility which will have markedly less power available than space stations.

Design Approach

To achieve the characteristics listed above, a concept was selected which uses PWM dc power into the thruster heater to control heater temperature to a preset reference value. Variations of this approach have been used previously and are described elsewhere.[6,7] An advantage of this approach is that heater thermal mass, instead of electronic components, is used to average the pulsed dc power. Another advantage is that the constant resistance, electrically isolated thruster heater can be tailored to the dc bus, making the controller design simple. No power bus matching transformer or cold start surge current limiting schemes are required.

The power bus is connected directly to the thruster heater through the PWM power transistor switch. EMI is reduced using a small inductor-diode-capacitor network to reduce thruster heater and heater connecting wire dI/dt and dV/dt levels. Current in the inductor branch of the network was chosen to be discontinuous. In addition, current rise and fall times were chosen to be small fractions of the total PWM period. These decisions have the advantages of: (1) reducing turn on switching losses to nearly zero, (2) limiting the commutating diode losses to a small value and, (3) limiting the inductor and capacitor size and mass.

Most of the work described here was done at a convenient demonstration frequency of 430 Hz. Limited testing was done at 2 and 4 Hz. The choice of PWM frequency is governed by several considerations, each of which is important only for a certain range of frequencies. For frequencies on the order of 1 Hz, an approach that may be suitable for a battery bus, the power bus must supply pulsed currents. Otherwise the input filter becomes very large. Another consideration at 1 Hz is that the control system transportation lag of the PWM is 1 sec. This constrains the control loop design so that transient performance is limited but probably adequate for most systems. At frequencies on the order of 1 kHz, the transportation lag is negligible. In addition, switching losses are mostly turn off losses and can be kept below 1 W for this 1 kW system. Inductor core losses in the discontinuous current mode can be less than 2 W. EMI producing dI/dt and dV/dt can be kept low because switching transitions can be on the order of 100 sec without affecting the current form factor (ratio of peak to average current) to any practical degree. At 1 kHz the input filter needed to limit reflected power line ripple will be larger than that for a typical 10 to 20 kHz spacecraft type buck regulator, but that is the only circuit that contributes significant mass.

Design Details

A functional diagram for a simple flight type power controller is shown in figure 3. The figure shows an input EMI filter, thruster heater, a dI/dt and dV/dt limiting network, and parallel power MOSFET switches used for PWM control of thruster heater current. A platinum resistance temperature sensor measured thruster heater temperature and a conventional control loop was used with a fixed frequency PWM. The breadboard implementation of this scheme used a thermocouple and thermocouple readout instead of the platinum resistance temperature sensor. This was done for thruster fabrication convenience. Unfortunately, this also limited the transient performance. The transfer functions necessary for control system design are given in Appendix A. The control circuit implementation used two operational amplifiers, one for error determination and one for proportional plus integral control. A standard PWM integrated circuit that enabled operation down to 1 Hz was the only other integrated circuit used. The circuit schematic and details are given in Appendix B. It should be noted that no effort was made to reduce turn off switching loss or select an optimum PWM frequency for this initial breadboard.

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TESTS

Loadbank Tests

The controller was tested with a nominal 5 Ω nichrome heater with an Inconel sheath connected in series with a 10 Ω power resistor used for convenience to simulate the thruster heater. A thermocouple with a readout was welded to the Inconel heater sheath and a thermocouple readout with an analog output was used for closed loop control. A small fan was used to vary the heat load and simulate variations of propellant flow rates. Controller operation was verified for 430 Hz and 4 Hz PWM frequencies. Operation at 2 Hz caused large output disturbances in certain of the laboratory power supplies that provided input power to the controller. The laboratory power supply control systems transient responses were inadequate under these pulse loading conditions.

Direct measurement of input and output power to determine power efficiency for the pulsed dc output was not practical using readily available standard instruments. Instead, component power losses were measured or calculated and tabulated in the Table. Breadboard power efficiency was 99 percent under conditions of 150 V input, 15 Ω load, 1 kW output and 430 Hz PWM switching frequency.

Thruster Tests

The power controller-thruster test configuration is shown in Fig. 4. The water feed system consisted of a stainless steel propellant reservoir, a regulated supply of nitrogen pressurant, a graduated sight glass for mass flow measurement, and a shut-off valve between the reservoir and the sight glass. This system supplied the water resistojet with liquid at a relatively constant inlet pressure. The mass flow rate through the system was controlled by the pressure difference across the flow restrictor at the resistojet. The resistojet chamber pressure varied significantly under transient conditions. The flow restrictor was capable of producing pressure drops of up to 1.6 MPa at a flow rate of 0.2 g/sec. This flow rate corresponded to a boiler chamber pressure of 0.5 MPa in the laboratory model water resistojet. Therefore, the flow restrictor provides an inlet pressure drop which is significantly larger than the absolute boiler chamber pressure at mass flow rates of interest. This tends to reduce the effect of variations in chamber pressure on the mass flow rate into the thruster. For example, a change in the boiler chamber pressure from 0.5 to 0.55 MPa produces a 3 percent reduction in the inlet pressure drop of 1.6 MPa, assuming the feed pressure remains constant. Since the mass flow rate into the thruster is proportional to the square root of the inlet pressure drop, a 10 percent increase in chamber pressure results in a reduction in mass flow rate into the thruster of only 1.5 percent. A solenoid valve located directly upstream of the flow restrictor provided for propellant shutoff. The proximity of the solenoid valve and flow restrictor to the injector channel minimized the liquid volume downstream of the valve. It was necessary to evacuate this volume each time the thruster was shut down before the thrust level dropped to zero.

The water used for all tests was distilled to remove impurities that might be deposited on thruster or feed system surfaces. Mass flow rate measurements were obtained using a graduated sight glass and the flow. Rates were held constant to within ±3 percent.

All tests were conducted using a vacuum facility measuring 1.1 m in diameter by 4.6 m long, and equipped with a mechanical blower backed by a rotary piston vacuum pump. Tank pressure was below 27 Pa (0.2 torr) during thruster operation at the maximum flow rate. The power controller temperature signal as well as the signal controlling power delivered to the thruster were recorded on a two channel chart recorder.

The recorded power control signal turned the heater power full on (1.4 kW at 150 V input) at a power control signal of 3.10 V and above, and full off at a power control voltage of 1.05 V and below. Power was nearly a linear function of voltage between 1.05 and 3.10 V.

Figures 5(a) and (b) show thruster heater current waveforms at partial and at full power. Figures 5(c) and (d) show turn on and turn off heater current transitions where heater dI/dt and, therefore, dV/dt have been minimized to reduce EMI.

Some initial thruster startup tests at 150 V input were tried without preheating the thruster. In one test, non-linear large signal system oscillations resulted with heater temperature excursions of nearly 500 °C. The oscillations appeared damped. The test was terminated after three cycles, 22 min. after startup. Evidently poor quality steam had reached the superheater. It was concluded that preheat was necessary for good quality starts.

A typical start up sequence, as well as transient responses to propellant flow rate changes, are shown in Fig. 6(a). Thruster and heater temperatures were 30 °C when power was turned on. With no propellant flow, the heater temperature overshoot was about 80 °C and there was also an underdamped oscillatory system response not typical of the transients introduced while propellant flowed. The frequency response data for conditions of no flow would show a higher thruster dc gain than with propellant flow because less power is needed to produce a given temperature change. This is at least a partial explanation for the underdamped transient response. Fortunately, however, enough gain and phase margin were available for the no propellant condition to maintain system stability. A propellant flow of 0.10 g/sec was started after a 7 min preheat. An arbitrary step change in propellant from 0.10 to 0.145 g/sec was introduced about 24 min after initial turn on and the resulting temperature change was too small for the recorder to show. Furthermore, it took about 4 min for the power to begin increasing. At 24 min after the propellant step increase, there was a precipitous small increase in power followed by a gradual decline. The controller maintained temperature close to 650 °C during this event. A step reduction in propellant flow rate to 0.095 g/sec showed a precipitous decline in power after 8 min. The temperature again remained close to 650 °C during this transient event. These power changes at constant temperature are thruster phenomena and may be related to two phase flow.

System responses to arbitrary step changes in the reference voltage and input voltage shown in Fig. 6(b) are much faster than the system response to step changes in propellant flow rate. Step reference changes of ±20 °C, and ±40 °C show small temperature overshoots and an overdamped system response. The same is true for ±10 V changes in the 150 V power source voltage. Propellant turn off resulted in two precipitous power changes where the temperature remained nearly 650 °C. The small (~0.03 V) higher frequency changes in the power signal trace are the result of the analog temperature signal changing in discrete 0.001 V steps.

DESIGN CONSIDERATIONS FOR AN ENGINEERING MODEL CONTROLLER

The effort described in this paper for the laboratory model thruster used a bus voltage of 150 V for convenience. A 28 V Bus Controller could employ some of the new hermetically sealed power MOSFET hybrid circuits now under development. Several power MOSFET transistor chips are connected in parallel complete with gate resistors and gate protection zener diodes. The resultant low on resistance would allow high efficiency to be achieved even for a 28 V bus. It is estimated that a 1 kW class heater controller operating from a dc bus on the order of 100 V could achieve a power efficiency greater than 97 percent based on the 99 percent breadboard efficiency and the addition of an input filter. Controller mass would depend predominantly upon the input filter which depends mainly upon the reflected current ripple specification.

CONCLUSIONS

A simple breadboard power controller operating from a nominally 150 V dc power source was designed and demonstrated with a new liquid-fed water resistojet. The laboratory model resistojet has an integrated vaporizer/superheater and uses a single heater element.

Thruster, temperature readout, and pulse width modulated (PWM) power circuit small signal transfer functions were experimentally determined for one set of operating conditions. Based on these transfer functions, a proportional plus integral controller transfer function was derived that provided conservative stability margins, and adequate steady state temperature error and transient performance. In addition, a thruster heater dI/dt and dV/dt limiting network was used to demonstrate a technique for reducing EMI.

The power controller maintained a constant heater temperature at or near a preset reference temperature by providing (PWM) dc power into the thruster heater. A thruster preheat with no propellant flow was required to achieve stable controller/thruster operation due to the two phase flow in the thruster.

Stable thruster heater temperature control and adequate transient response were verified for initial power turn on, preheat, step changes in propellant flow, input voltage and temperature setpoint. Initial turn on temperature overshoot from room temperature to a 650 °C setpoint was 80 °C. Breadboard power efficiency was estimated from direct measurements and calculations to be 99 percent at 1 kW. Component mass was about 0.4 kg excluding an input filter necessary for spacecraft integration. Based on the breadboard tests, it is judged that a 1 kW class liquid-fed water resistojet power controller meeting typical spacecraft thermal, EMI and vibration specifications can be developed having power efficiencies in excess of 97 percent and a packaged mass of less than 3 kg.

APPENDIX A - TRANSFER FUNCTIONS

This appendix describes the experimental determination of the small signal transfer function of the combined thruster, PWM and temperature readout using a gain/phase (Bode) diagram. A controller transfer function was then selected, using conventional Bode diagram compensation techniques, which achieved the desired steady state and transient performance while maintaining adequate closed loop stability margins. The experimentally determined PWM/thruster/temperature readout transfer function was factored into three transfer functions using suitable assumptions. This was done to establish the approximate thruster transfer function.

The test configuration was the same as described earlier and shown in Fig. 4, except for the addition of a low frequency signal generator with an adjustable offset. Only the PWM portion of the control circuit was used. The signal generator was connected to the PWM control port where a signal from 1.05 to 3.1 V provided a nearly linear power change from 0 to 1.4 kW at 150 V input. The PWM frequency was 430 Hz. The signal generator dc offset control was used to set the thruster steady state temperature to about 650 °C with the water propellant flow rate maintained close to 0.17 g/sec. An ac power control signal from 0.0063 to 1.9 rad/sec (0.001 to 0.3 Hz) was superimposed on the signal generator dc offset. This power control signal, v_M, as well as the voltage corresponding to temperature, v_T, were simultaneously recorded with the strip chart recorder. The data were plotted in the Bode diagram, Fig. A1. The commercial temperature readout resolution was limited because the analog output changed in discrete steps of 0.001V/c°. For this reason, the data at 1.9 rad/sec (0.03 Hz) and above were inaccurate and not plotted.

The phase shift calculated from the magnitude plot, Fig. A1(a) reaches a maximum value of -180.° (The calculated phase shift is not shown.) At the higher frequencies, the experimentally determined phase shift figure A1 (B), rapidly increases to beyond -260.° This phase discrepancy is accounted for by a transportation lag, $T_d = 1.4$ sec, calculated from the Bode diagram. The delay was due mainly to the temperature readout. This commercial temperature readout incorporates a conventional dual slope integrator to convert the analog thermocouple signal to a digital signal for use in a digital numerical readout. This digital signal is also converted to a separate 1 mV/°C analog output. The delay was specified by the manufacturer as 0.3 sec at low magnitudes to a maximum of 1.5 sec. Of course, this complication would not have occurred had the thruster incorporated a platinum resistance temperature sensor.

The transfer function determined from figure A1 for the PWM, thruster and temperature readout was:

$$G_a(s) \simeq \frac{0.18e^{-1.4s}}{\left(\frac{S}{0.032} + 1\right)\left(\frac{S}{0.33} + 1\right)} \qquad \text{(A1)}$$

Selection of the controller transfer function for $G_a(s)$ is constrained by the need to accommodate the phase shift introduced by the factor $e^{-1.4s}$. Conventional control system design would simply maintain the open loop magnitude below 0 dB at frequencies where phase shift is changing rapidly. This was done and overcame the potential instability introduced by the transportation lag. However, the resulting system had a narrow bandwidth resulting in limited transient performance.

For this breadboard, a proportional plus integral controller was chosen. The infinite dc gain of integral control results in the controlled temperature being exactly equal to the reference temperature under steady state conditions. Proportional control provides gain at the higher frequencies to give adequate transient response.

Based on the Bode diagram, figure A1, the transfer function for the proportional plus integral controller was chosen to be:

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$$G_c(s) = \frac{\frac{S}{0.033} + 1}{\frac{S}{0.5}} \quad \text{(A2)}$$

for conservative calculated phase and gain margins of approximately 70° and 18 dB, respectively.

The open loop system transfer function is then:

$$G(s) \approx \frac{0.18e^{-1.4s}}{\left(\frac{S}{0.5}\right)\left(\frac{S}{0.33} + 1\right)} \quad \text{(A3)}$$

An approximate expression for the thruster transfer function can be obtained by assuming all the transportation lag is due to the temperature readout and by factoring the PWM and the temperature readout transfer functions out of equation (A1). The PWM transfer function is:

$$G_p(s) \approx \frac{V^2}{2.1R} \quad \frac{W}{V} \quad \text{(A4)}$$

For V_{in} = at 150 V, and R ≈ 15,

$$G_p(s) \approx 700 \quad \frac{W}{V} \quad \text{(A5)}$$

The temperature readout transfer function is:

$$G_R(s) \approx 0.001e^{-1.4s} \quad \frac{V}{^{o}C} \quad \text{(A6)}$$

Therefore, the small signal thruster transfer function is:

$$G_T \approx \frac{0.3}{\left(\frac{S}{0.032} + 1\right)\left(\frac{S}{0.33} + 1\right)} \quad \text{(A7)}$$

for conditions of 650 °C heater temperature, 0.17 g/sec propellant flow.

APPENDIX B - CIRCUIT DETAILS

The power controller breadboard circuit schematic is shown in Fig. B1. For thruster fabrication convenience, a thermocouple and thermocouple readout were substituted for a simple platinum resistance temperature sensor. The choice of some of the parts was based on availability more than performance.

The pulse width modulation controller is an integrated circuit SG1526. This controller was selected for the initial design since it permitted system testing at PWM frequencies as low as 1 Hz. However, the SG1526 had some minor disadvantages for this application. They were: (1) The transconductance error amplifier bias currents were too high to achieve the time constants required to compensate the control loop. Therefore, the SG1526 error amplifier was connected as a voltage follower with a gain of 1, and (2); For the required single ended power transistor gate drive used in this breadboard, fast power transistor turn off was not possible without incorporating additional circuitry. It was decided to accept the 2.1 W turnoff loss at 430 Hz to keep this initial breadboard simple.

An LM108 was selected for the error amplifier since it has a low offset drift and small input bias current change with temperature. The proportional plus integral controller time constant implementation required an amplifier with low input bias current so an LM108 was used here also. The output of this stage was clamped to voltages near the upper and lower thresholds of the PWM control input. This was done to limit the voltage swing of the integrator capacitor.

The 100 μH inductor, commutating diode and 0.1 μF capacitor were used to limit dI/dt and dV/dt into the thruster heater to demonstrate a reduced potential for EMI at high frequencies.

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TABLE - BREADBOARD CONTROLLER POWER LOSS TABULATION

[Power efficiency at 1 kW = 99 percent.]

Item	Power loss, W	Method obtained[a]
±15 V bias power	1.2	Measured
Transistor conduction	2.9	Calculated
Transistor turn on	0	Measured
Transistor turn off	2.1	Measured
Inductor copper	1.3	Calculated
Inductor core	1.8	Estimated from limited Manufacturer's data
Commutating diode	0.04	Calculated
Capacitor ESR	0	Calculated
Total losses	9.3	

[a]Under conditions of 150 V input, 15 Ω load, 1 kW output, 430 Hz switching frequency.

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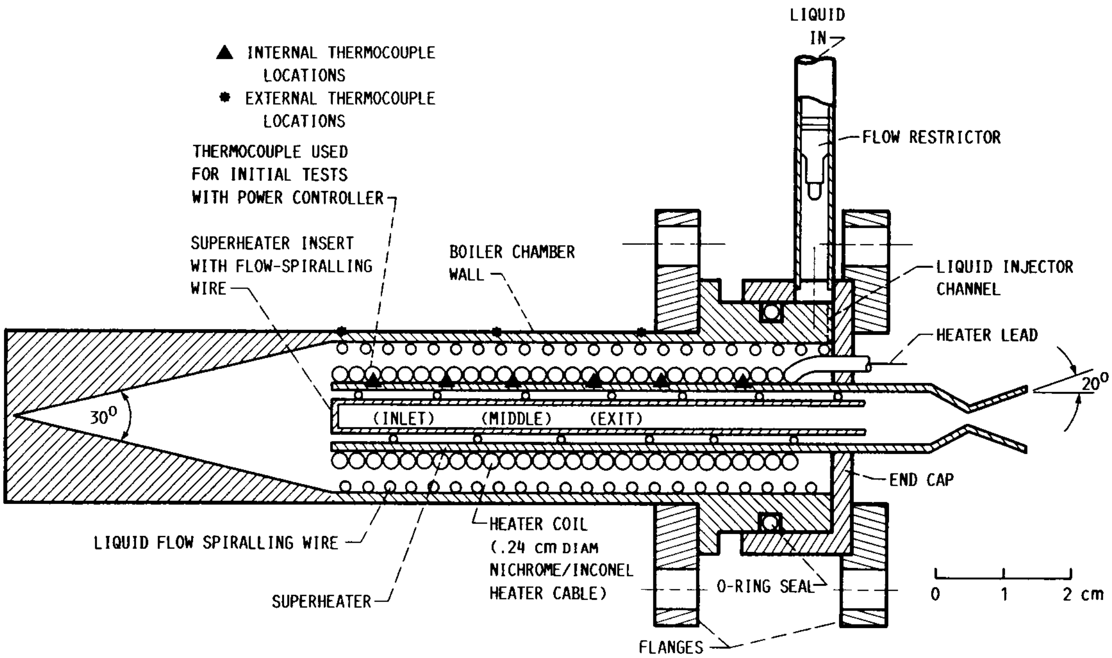
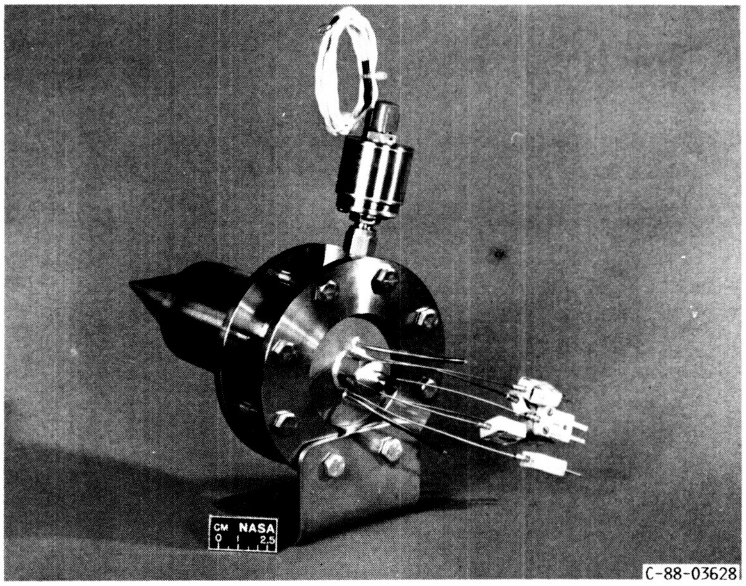
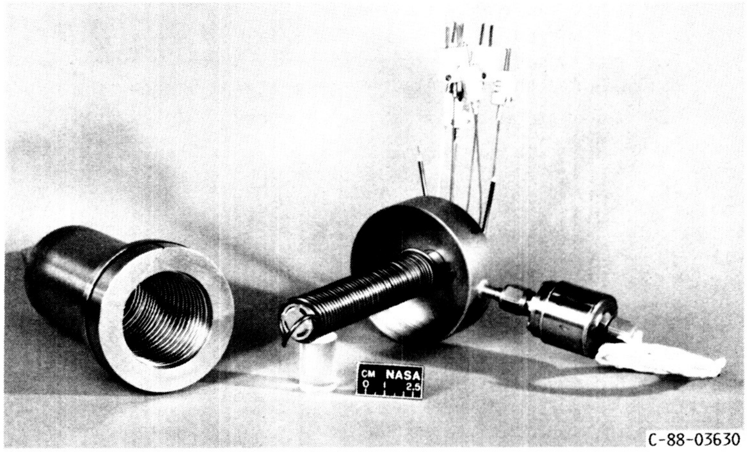


FIGURE 1. - SECTIONAL DRAWING OF LIQUID-FED WATER RESISTOJET (ENHANCED CYCLONE VAPORIZER WITH NOZZLE ADDED).



(A) THRUSTER ASSEMBLED.



(B) THRUSTER DISASSEMBLED.
FIGURE 2. - LIQUID-FED WATER RESISTOJET.

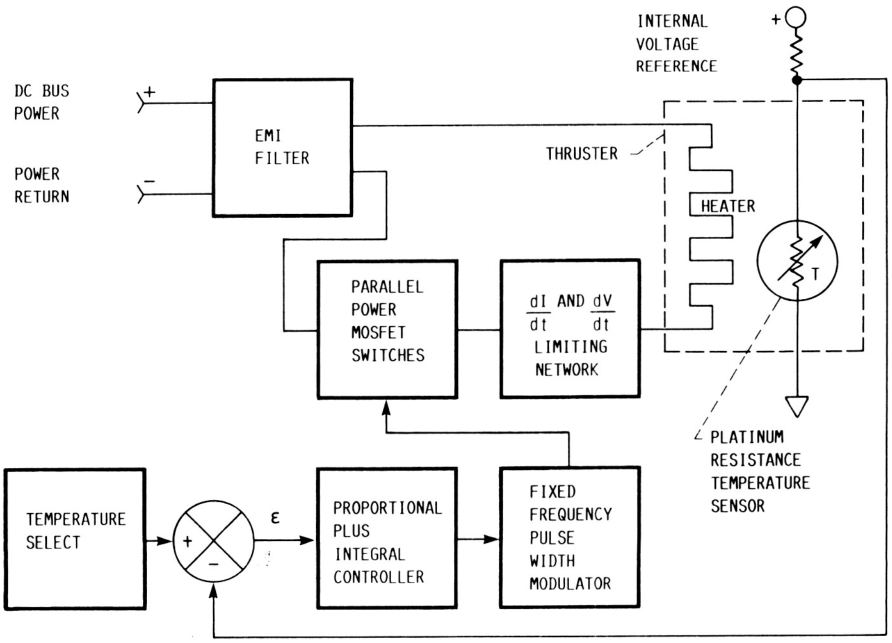


FIGURE 3. - FUNCTIONAL DIAGRAM SIMPLE FLIGHT TYPE LIQUID RESISTOJET POWER CONTROLLER.

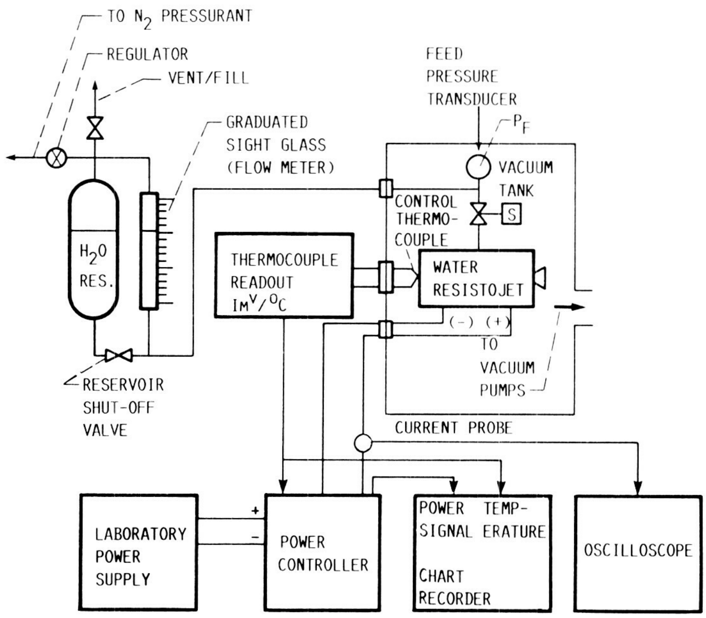


FIGURE 4. - WATER RESISTOJET POWER CONTROLLER TEST CONFIGURATION.

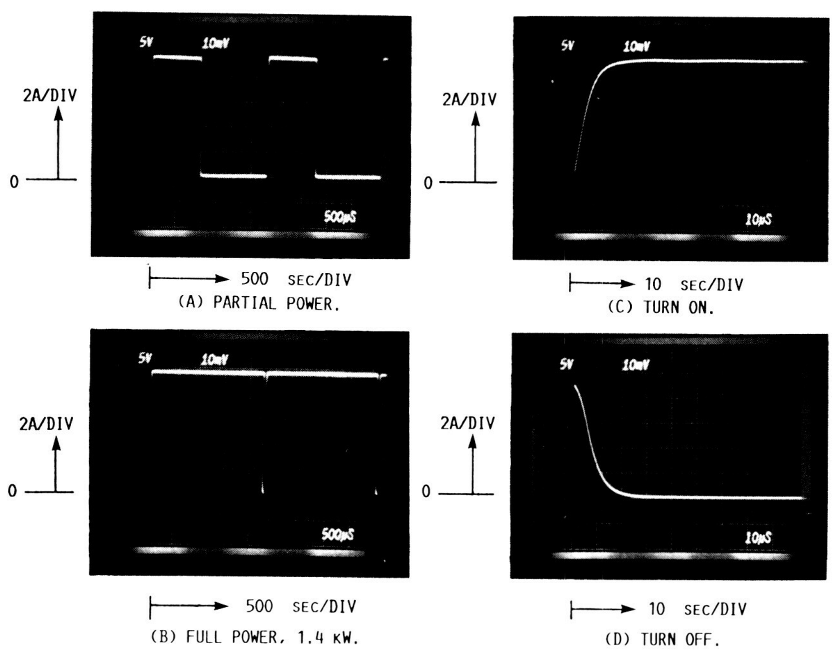


FIGURE 5. - THRUSTER CURRENT WAVEFORMS, 150V INPUT, APPROXIMATELY 650 ^oC HEATER TEMPERATURE

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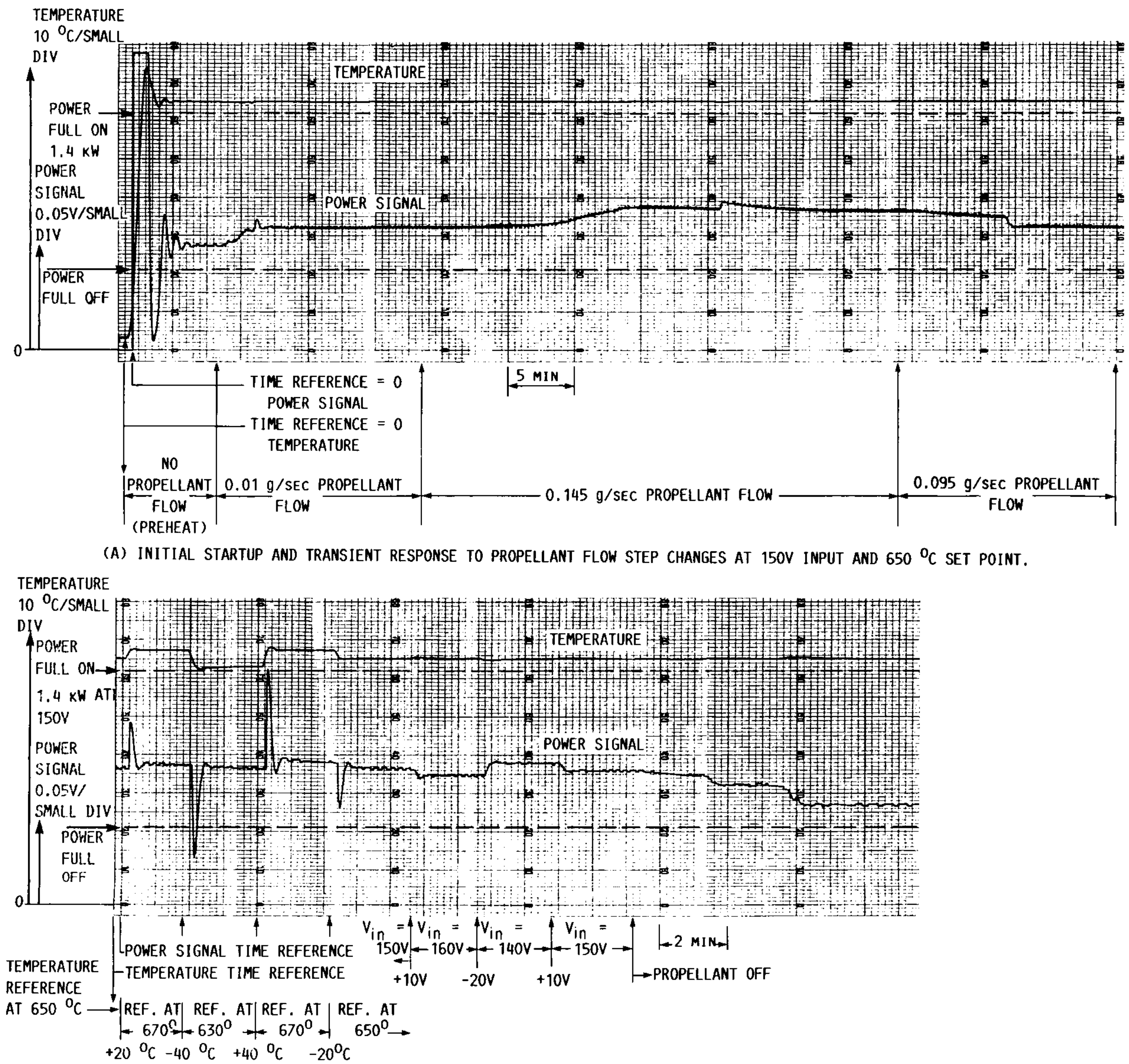
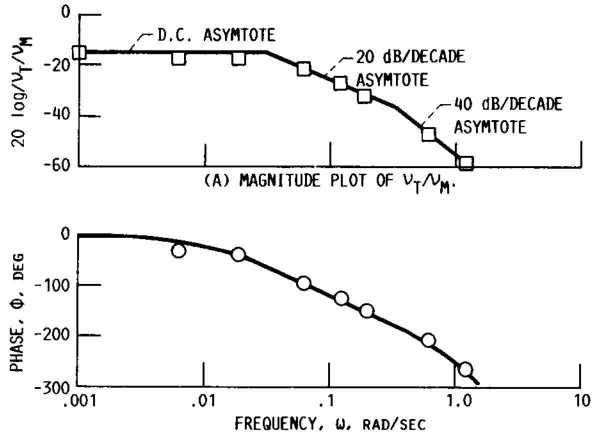


(A) INITIAL STARTUP AND TRANSIENT RESPONSE TO PROPELLANT FLOW STEP CHANGES AT 150V INPUT AND 650 °C SET POINT.

(B) TRANSIENT RESPONSES TO STEP CHANGES IN TEMPERATURE CONTROL REFERENCE AND INPUT VOLTAGE WITH PROPELLANT FLOW AT 0.145 g/sec AND PROPELLANT OFF.

FIGURE 6. - CONTROL SYSTEM AND THRUSTER INITIAL STARTUP AND TRANSIENT RESPONSES TO STEP CHANGES IN PROPELLANT FLOW RATE, INPUT VOLTAGE AND CONTROL TEMPERATURE REFERENCE.



(B) PHASE PLOT OF ν_T/ν_M.

FIGURE A1. - BODE DIAGRAM OF COMBINED THRUSTER, TEMPERATURE TRANSDUCER AND PULSE WIDTH MODULATOR FOR CONDITIONS OF 150V INPUT, 0.17 g/SEC PROPELLANT FLOW RATE, AND HEATER TEMPERATURE ABOUT 650 $^{\circ}$C.

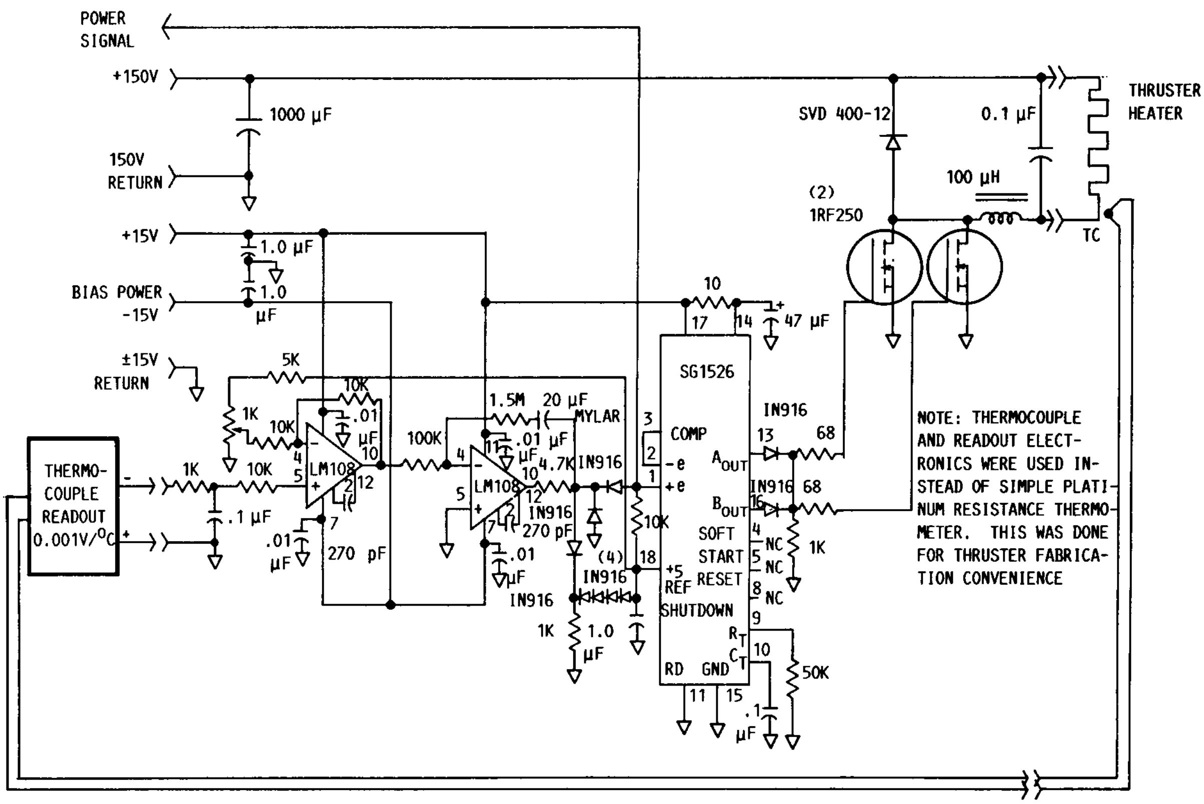


FIGURE B1. - SCHEMATIC DIAGRAM LIQUID-FED WATER RESISTOJET POWER CONTROLLER BREADBOARD.

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16. Abstract

A simple breadboard power controller was designed and demonstrated for a new liquid-fed water resistojet. The one piece laboratory model thruster has an integrated vaporizer/superheater using a single heating element. Heater temperature was maintained at or near a preset reference value with the closed loop controller providing pulse width modulated (PWM) dc power into the thruster heater. A combined thruster, temperature readout, PWM transfer function was experimentally determined. This transfer function was used to design a proportional plus integral controller that demonstrated zero steady state error, conservative stability margins and adequate transient response to step changes in propellant flow rate, input voltage and temperature reference. Initial turn on temperature overshoot from room temperature to a 650 °C setpoint was 80 °C. In addition, EMI was alleviated by reducing heater dI/dt and dV/dt using a simple diode-inductor-capacitor network. Based on limited initial tests, thruster preheat with no propellant flow was necessary to achieve stable system operation during startup. Breadboard power efficiency was 99 percent at 1 kW, and component mass was 0.4 kg excluding the power loss and mass of an input filter required for spacecraft integration.

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