Simulation of a Ground Facility for Testing Ramjets Under Flight Conditions

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Theme

A CONTROLLED Flow (CONFLOW) facility is being built to test air-breathing propulsion systems and airframes in simulated flight missions using full-scale hardware. CONFLOW provides reconstituted air to the subsonic duct of a combustor to represent flight variations of flow, total temperature, and pressure. Stored oxygen, nitrogen, and butane are reacted to produce the desired temperature and composition. A series of pressure reductions with combustion in an air generator with nozzle delivers controlled flow to the ramjet combustor.

This Synoptic describes the system and its development through the use of analog simulation to achieve necessary flow control. The advantages of continuing analog simulations throughout the development plan are set forth.

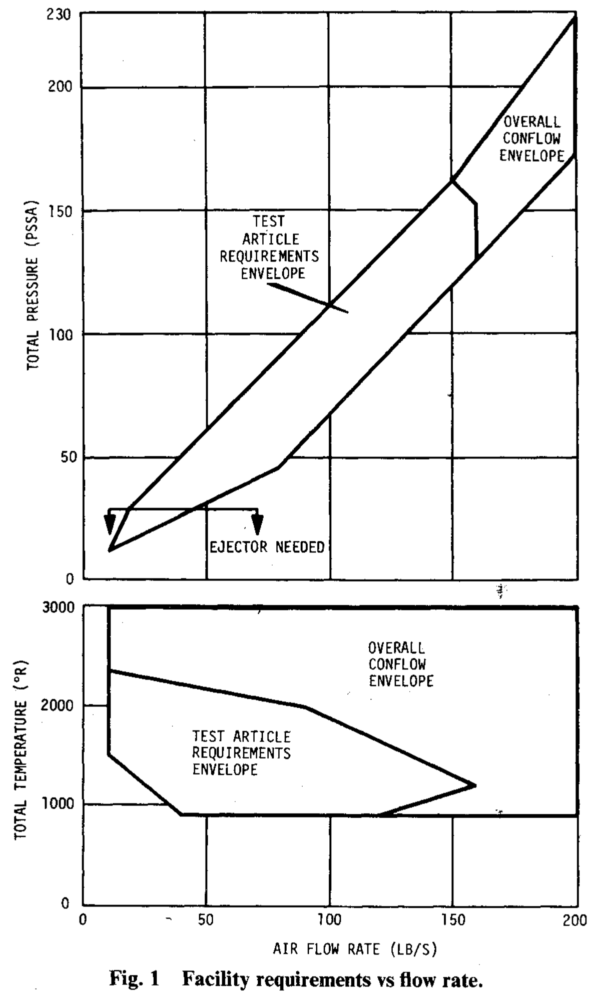

Fig. 1 Facility requirements vs flow rate.

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Index categories: Computer Technology and Computer Simulation Techniques; LV/M System and Component Ground Testing; Air-breathing Propulsion, Subsonic and Supersonic.

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CONFLOW provides a closely controlled amount of reconstituted air to the subsonic duct of the test article, representing airflow delivered to the combustor. A paper presented by the author[1] showed that equivalent air produced by combustion of propane, oxygen and nitrogen yields ramjet performance from 0% to 2% below real air over a wide range of flight conditions. The fuel subsequently has been changed to butane for vapor pressure reasons; however, the predicted engine performance from computer studies remains unchanged from propane performance.

A study of many trajectories for an integral, rocket-boost, ramjet-sustain type of missile yields an envelope of total pressure and total temperature requirements as shown in Fig. 1. Initially, CONFLOW will have the capability for single-point testing. Planned future developments include operation anywhere in the envelope plus computer-controlled, real-time simulation of the air parameters, aerodynamic heating, and cooling simulation, mechanical loads simulation, altitude simulation by use of an ejector, and solid propellant booster-to-ramjet combustion transition.

System description: The CONFLOW system requires nitrogen, oxygen, and butane flow systems, each of which is controllable. All of these flow paths meet in the air generator at combustor pressure as shown in Fig. 2.

The gases are stored at 6000 psi. The wide range of conditions requires that the pressure in each line be controlled in three steps: two regulators and a control valve. From manifolds the gas flows are split up by orifices into flow to the mixer and flow to the cooling shroud. The bulk of the gas is passed through slots in the cooling shroud to achieve film cooling of the air generator.

The gas in the mixer becomes the oxidizer for the butane fuel which is fed through two sets of injectors to accommodate the wide conditions imposed on CONFLOW. Triethylboron (TEB)

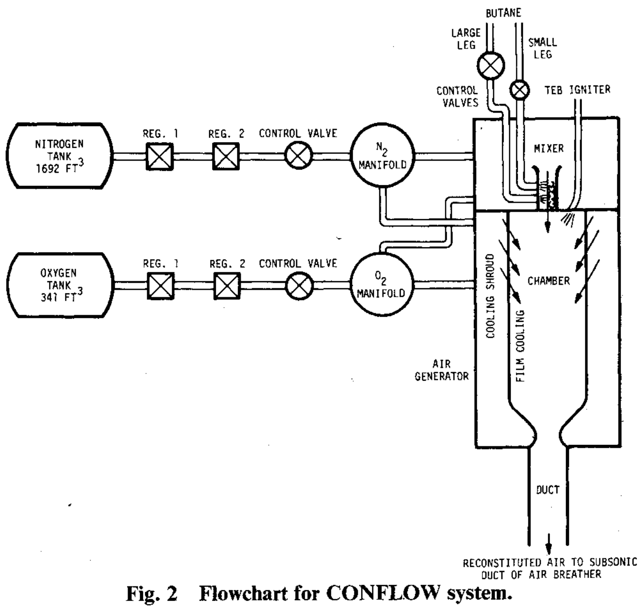

Fig. 2 Flowchart for CONFLOW system.

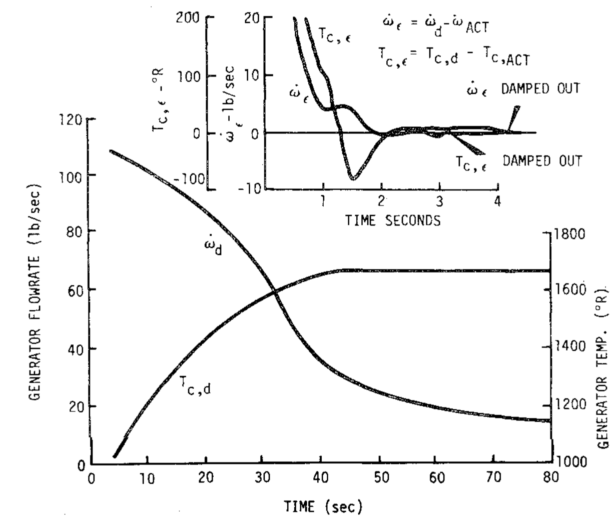

Fig. 3 Low level launch and climbout.

is used as an igniter. The ratios of the three streams are closely controlled to deliver a gas of the same oxidizing potential as natural air, 20.95 mol percent. This reconstituted air is directed to the subsonic duct of the air-breathing engine to be tested.

A steady-state characterization established sizes and ranges of pipes, regulators, control valves, injector areas, orifices, and nozzles. Pressure laws for each regulator in terms of system flow were determined. Two analog computer consoles were used to simulate the entire CONFLOW system. The major parts of the model are a nitrogen leg, oxygen leg, and butane leg. Also simulated are igniter, mixer, cooling shroud, and chamber areas. The dynamic simulation completed the CONFLOW design by determining the elements of flow and temperature control plus compensations for each regulator and control valve. The model is then tested against anticipated needs. The facility design must remain stable and exhibit response times sufficiently shorter than the missile combustor system to contribute negligible lags in the total system simulation. System specifications require that actual flow be within $\pm 3\%$ of desired flow, and actual temperature within $\pm 10\%$ of desired value.

The simulation was tested against eight single point runs in the test article requirements envelope, three additional single point runs to get the remaining corners of the over-all envelope, an endurance run to determine system limits, plus four trajectory characterizations.

Valve dynamics and actuator design: The controlled flow feature of this facility is directly attributable to valve and regulator dynamics. The fast responses required of CONFLOW valves and regulators dictate hydraulic actuators for valve operation. A separate analog simulation was used to determine the hydraulic actuator system for each valve. The analog simulation determined the actuator cylinder bore size and stroke, servo-valve flow capability, servo-amplifier gain, hydraulic accumulator capacity, and hydraulic pump requirements such that each actuator has the necessary response and force capabilities for the CONFLOW system.

The results of the actuator simulation are detailed in the full paper. A 34 gpm hydraulic pump was installed to meet the maximum possible pump requirements as determined by a 2Hz duty cycle for all valves operating simultaneously. The valve actuation times were used in the over-all CONFLOW simulation in a second-order, rate-limited transfer function. As actual test data for valve operation become available, it is substituted in the over-all simulation.

Complete system simulation: The best compensation for the valve and regulators was determined to be of the proportional plus integral mode

$$G = K_1 + K_2/S \tag{1}$$

where G = transfer function, K_1 and K_2 are gain constants, and $S = d/dt$. However, to cut down on the phase lag of the CONFLOW system, it was necessary to change the compensation of the control valves to straight integral mode ($K_1 = 0$).

During the simulation, it was found necessary to change the time constant on the first-order lag of the butane flowmeter from 1.5 sec to 0.15 sec. The original flowmeter, which was also contributing to phase lag, had to be reordered with faster response.

The original simulation generated command flows of nitrogen, oxygen, and butane based on differences between actual and desired values of chamber temperature, T_c, and total flow, $\dot{w}_{out}$. The difference was passed through proper compensation to yield corrective values of temperature and flow; however, sequencing problems which led to amplifier overloads required that the corrective values of temperature and flow be replaced by the desired values. Thus the "best" controller turned out to be uncompensated.

Results of system simulation: Most of the console time was devoted to determining the elements of control to produce desired flows and temperatures without excessive ringing or oscillations of actuator strokes, pressures, or temperatures. No set of compensation constants was the best for all conditions, but it was a goal of the simulation to find one set of constants for the entire test article requirements envelope.

In the single point runs, which essentially are ignition tests, the time to bring generator flow to $\pm 3\%$ of the nominal flow rate varies from 300 msec to as high as 8 sec at the lowest flow rate of 10 lb/sec. Chamber temperature is brought to $\pm 10\%$ of nominal in 600 msec to 7 sec. The percentage of oxygen in the generator is easily held at $23 \pm 1\%$ by weight

Close attention was paid to all analog traces for oscillations of valve actuator strokes. The worst case was a sinusoidal oscillation of 10Hz in the nitrogen upstream regulator. The maximum amplitude of this ringing is only 7% peak-to-peak and is damped out in 0.5 sec. This represents a much smaller demand of the oil from the accumulator than that allowed in the design simulation.

With time allowed for filling volumes downstream of the shutoff valves for butane and TEB, the proper starting sequence is as follows.

1) At $t = 0$ sec, commands to butane and nitrogen control valves.

2) At $t = 5$ sec, commands to igniter and oxygen control valve.

3) At $t = 6$ sec, igniter off.

An endurance run was made to determine any drawbacks in operating CONFLOW near the lower limit of tank pressure. For a high flow rate run of 160 lb/sec, the analog model maintained steady oxygen and nitrogen flow to the generator down to tank pressures of 1800 psia for nitrogen and 1300 psia for oxygen, both pressures well below the specification value of 2000 psia.

Several flyout trajectories were flown to determine the ability of the CONFLOW system to deliver properly conditioned air in a constantly varying environment. Figure 3 shows a trajectory of a low-level launch with a climbout. This trajectory covers a gamut from high to low flow and a traverse from low to high temperature. Figure 3 also shows that errors were quickly damped out: temperature error in 3.1 sec and flow error in 4.3 sec.

Conclusions: Analog simulation was found to be a valuable design tool. All of the compensations and controllers were determined against CONFLOW specifications. The results of the simulations indicate that the basic concepts of CONFLOW can be met. Not only is the analog model an important design tool, but by keeping the simulation patchboards in line with test data, the analog computer then becomes an inexpensive test stand in its own right.

References

[1] Mitchell, W., "Propellants Selection to Provide an Air Simulant for Hot Gas Ground Testing of Ramjets," AIAA Paper 72-1070, New Orleans, La., 1972.