Application of Pulse Facilities to Inlet Testing

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Experiments in both a shock tunnel and hotshot have proven the feasibility of using pulse facilities for advanced inlet testing. An internal contraction inlet tested at a hypersonic Mach number in a hotshot facility was successfully started at its maximum running contraction and with a choked exit nozzle. Close correlation with wind-tunnel data was achieved with the throttle in both supercritical and subcritical positions. An unthrottled hypervelocity inlet was started in a shock tunnel at a contraction ratio of 25/1. Surface pressures and friction gages were used to determine performance. Significant time-dependent flow adjustments were detected in both tests. Additional tests were performed in the hotshot using the exothermic decomposition of nitrous oxide as a heat supplement. Near-instantaneous reactions were achieved, resulting in pressures much higher than those attainable by arc heating alone. NO_2 contamination was detected but was found to be an inverse function of N_2O load pressure and concentration. Theoretical calculations indicate that small amounts of hydrogen can produce an additional large pressure increase. The usefulness of pulse facilities in obtaining real gas and wall cooling data is discussed, and an inlet model designed for this purpose is briefly described.

Introduction

In recent years the pulse facility as a practical and profitable testing tool has become a reality. Sufficient data have been gathered at a number of facilities to prove its reliability and accuracy in obtaining external pressure, heat transfer, and force information.

The pulse facility offers many advantages. In general, the cost of construction and operation are lower than in other types of facilities. Practically any Mach number may be obtained and at pressures and temperatures considerably higher than can be achieved in other facilities. The disadvantage of short run times is being lessened by the continuing development of fast-response instrumentation. Problems such as Mach number and enthalpy profiles, heat loss, particle contamination, and nozzle erosion are still very real, but sufficient experience has been accumulated to relegate them to operational and developmental problems rather than fundamental uncertainties.

With the advance of air-breathing powerplants into the hypersonic and hypervelocity regimes, the pulse facility becomes also of interest for inlet testing. Consequently, many new questions must be answered and new areas explored. In contrast to the external situation, an inlet must pass the air through a contracting duct, slowing it to the extent that real gas imperfections become significant. In addition, considerations such as contraction, geometry variation, bleed, wall cooling, and boundary layer are of critical importance in inlet development. The present paper discusses experimental and analytical work that was undertaken in order to investigate the feasibility of pulse testing of inlets and to develop new techniques and approaches applicable to this type of testing.

Applicability of Pulse Facilities to Inlet Testing

Three questions are particularly relevant to pulse testing of inlets:

1) Can steady-state flow (including boundary-layer adjustments and heat-transfer rates) be established in the throat and subsonic diffuser in the short run times available?

2) What is the accuracy of the data obtained? Are pulse facility and wind-tunnel data compatible?

3) What are the starting criteria? Can the inlet be started in a running position, or is a moving component essential?

To investigate these questions and to develop techniques for pulse testing, the Marquardt Corporation conducted two separate tests, one in the Marquardt hotshot facility and the other in the Cornell Aeronautical Laboratory 48-in. shock tunnel. The hotshot model was an axisymmetric, semi-isentropic spike design. The centerbody could be translated axially to vary the internal contraction, and an exit throttling plug was provided to control the pressure level in the plenum. The model had been extensively tested in a conventional wind tunnel, thus providing comparative data. The hotshot tests were made at a hypersonic Mach number at the identical pressure and temperature employed in the wind tunnel. The shock-tunnel model was similar in design, but was longer because of its hypervelocity application, and no exit nozzle was provided. Tests were made at hypervelocity Mach numbers at nominal temperatures and pressures. A sketch of the two inlets is presented in Fig. 1. The hotshot instrumentation consisted entirely of pressure transducers whereas that of the shock tunnel included both pressure transducers and friction gages.

Prior to the hotshot tests, the model, instrumentation, and facility were analyzed in order to predict starting characteristics, tube lags, run times, and pressure decays. It was concluded that tube lags would in no case exceed 1 msec. The tests indicated that this was true, and the experimental

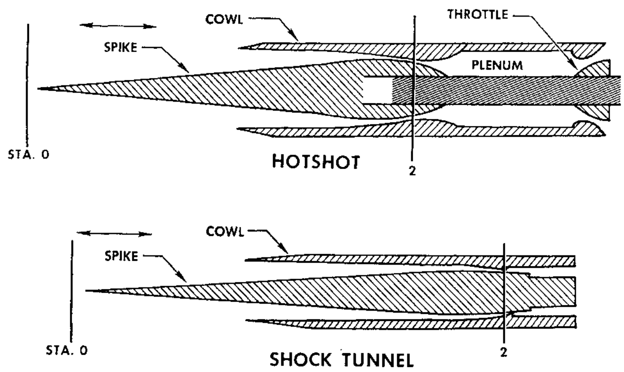

Fig. 1 Sketch–test inlet models.

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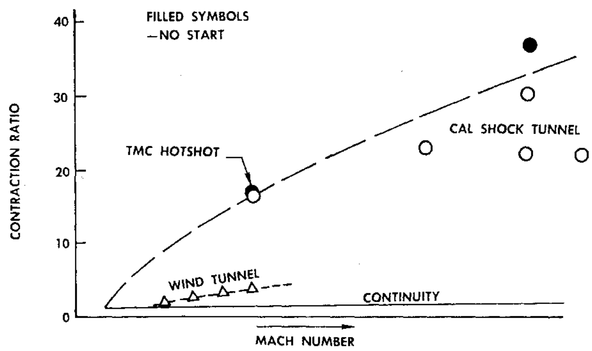


Fig. 2 Inlet starting characteristics.

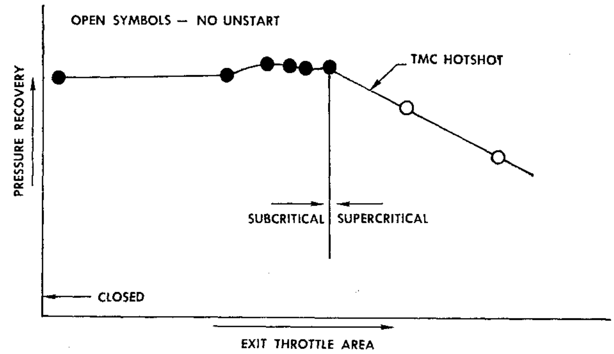


Fig. 4 Effect of throttle position.

decay rates and run times were found to be close to the predicted values.

In steady flow, continuity considerations indicate that an inlet is self-starting at contraction ratios of no greater than 2/1. Actual wind-tunnel models have restarted at ratios as high as 4/1, but this value is still far short of the contractions needed for high internal contraction inlets. These inlets, in contrast to external compression inlets, have therefore required some movable starting device. This would, of course, present a serious problem in pulse testing. Analytical studies of the pulse flow process, however, indicated that internal contraction would be no barrier to inlet starting. Although this was not rigorously proved, one-dimensional analyses of several logical starting shock positions showed that in each case the shock moved aft relative to the inlet. Subsequent inlet tests in both facilities confirmed this analysis, as can be seen in Fig. 2. Moreover, it appeared from cowl pressure readings that, even when contraction ratios greater than those attainable in steady-state facilities were tested, the initial pulse still passed through the inlet throat, starting the inlet momentarily. The over-contraction then expelled the shock.

From this behavior it would be expected that full running contractions could be successfully tested in pulse facilities. Figure 3 presents a plot of pressure recovery vs contraction ratio for the hotshot tests. Included is corresponding data from two separate wind-tunnel tests of the same model. The scatter in wind-tunnel pressure recovery data is seen to be larger than that between wind tunnel and hotshot. In addition, the maximum obtainable contraction ratios from both sources are in close agreement. Additional runs in the hotshot indicated excellent repeatability.

The use of a throttling plug introduces a second throat for the starting shock to negotiate. This, again, was no impediment, as can be seen in Fig. 4. With the throttle in a supercritical position (open symbols), the inlet remained started during the entire run. At the critical throttle position, the plenum pressure built up slowly until the inlet shock was expelled. Progressively closing the throttle resulted only in shortening the time to shock expulsion. At critical and nearly-closed throttle settings, the inlet unstarted after 37 and 8 msec, respectively. The difference in recorded pressure recovery was, however, less than one percentage point, indicating that the unstart process was a result of plenum chamber filling, rather than shock reflection. Since filling the plenum chamber would force the terminal shock train forward in precisely the same manner as closing the throttle in a steady-state wind tunnel, it appears that precise duplication of a wind-tunnel throttle traverse can be achieved with one subcritical setting in the hotshot. This is borne out by Fig. 5 in which P_4, a pressure just aft of the inlet throat, is plotted against the plenum pressure. Thus, time as a factor is eliminated. P_4 is not affected by increasing plenum pressure until the terminal shock train reaches that point. It then increases as a function of plenum pressure. The wind-tunnel curve is plotted from a series of discrete data points. Essentially the same curve is obtained from a single hotshot run.

This filling phenomenon, which so closely simulates wind-tunnel operation, presents many opportunities for time- and money-saving techniques. For example, it may be possible to devise a large, sealed plenum to obtain mass flow measurements.

The use of pressure and friction gages on the forward surfaces of the models provided valuable information on the inlet starting characteristics. A consistent sequence of events, modified by the individual circumstances, was detected and from this a starting process defined. As the initial shock passes through the inlet, it leaves a transient flow and boundary situation. Equilibrium conditions must then be established throughout the inlet before completely valid data can be obtained. The walls must achieve a steady (or at least quasi-steady) heat-transfer rate, and the boundary layer has to adjust to this condition as well as to its own downstream influences. In the hotshot tests, if boundary-layer separation was encountered, this adjustment occasionally required a considerable time period, as illustrated in Fig. 6 for two

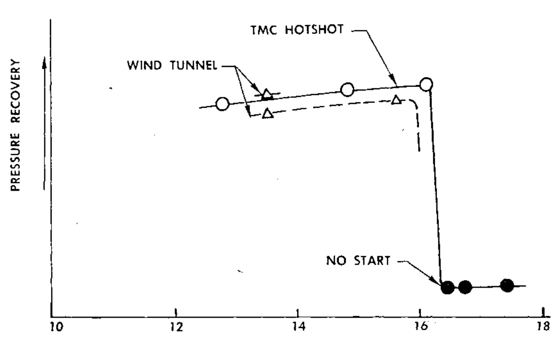


Fig. 3 Effect of contraction.

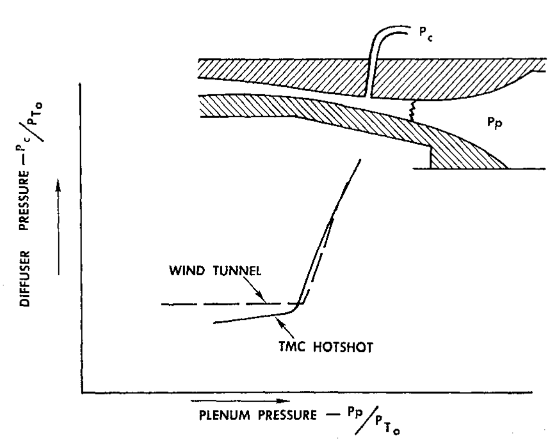


Fig. 5 Effect of back pressure.

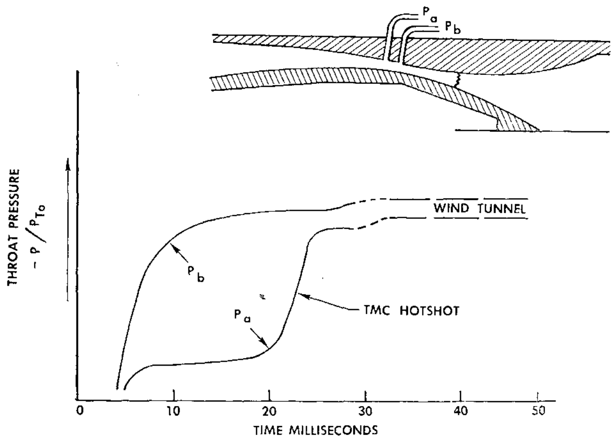


Fig. 6 Time dependency.

pressure taps just forward of the inlet throat. In this instance, about 25 msec were required for these pressures to stabilize. Related adjustment phenomena were also detected with the use of friction gages in the shock-tunnel tests. In these tests, the downstream influence of the throat normal shock was not present, but low Reynolds numbers and attendant flow separations were. At the lowest contraction ratios tested, the flow was normally attached, but, as the contraction ratio was increased, a stable separated region tended to form ahead of the throat. This separation was apparent within 2 msec of the start of the run and spread until it reached a steady value. Increasing the contraction ratio further tended to increase the length of separation, and, at the highest contraction ratios, the separation spread to the throat and unstarted the inlet. On a few occasions, it was still spreading when the run was terminated after about 5 msec. This separation phenomenon was the only transient condition encountered in the shock tunnel, and it appeared to be related to both low Reynolds number and unstart situations. The nontransient data were straightforward and consistent with wind-tunnel results. It is evident, however, that transient phenomena that can profoundly affect test results can occur in both shock tunnels and hotshots and that they can be detected with present instrumentation.

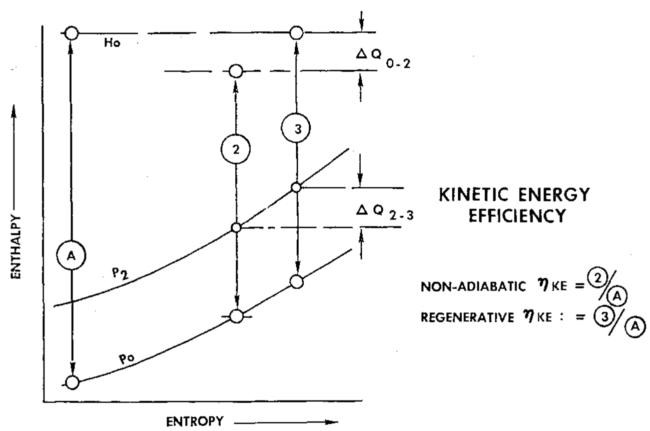
Determination of Hypervelocity Inlet Performance

When an exit throttle is provided, plenum Mach numbers on the order of 0.1 can be achieved and a pressure recovery simply measured. However, when no throttle is provided and the flow remains supersonic throughout the inlet, a different approach must be made to measuring and defining inlet performance. Of particular importance are the flow properties at the inlet throat. With hypervelocity flow, pressure recovery becomes difficult to measure directly. This is true both because of severe flow property gradients and because of geometrical considerations such as the relative sizes of flow passages and measuring probes. For this case it is more convenient to measure inlet performance in terms of throat stream thrust and energy level, which can be inserted directly into cycle analysis studies or used to obtain rating parameters such as kinetic energy efficiency (η_{KE}) and energy conversion efficiency (K_D). Flow distortion as a separate parameter would also be useful.

In determining stream thrust at the throat, the inaccuracies associated with direct measurements are often of larger magnitude than the performance differences being sought. An indirect approach is to subtract the total internal drag from entering stream thrust. Since this drag is on the order of 10% of the thrust, much larger measuring errors can be tolerated. This approach was adapted in the shock-tunnel tests by combining the results of static pressure and skin-friction measurements. Seventeen "conventional" Cornell Aeronautical Laboratories (CAL) piezoelectric gages on the cowl and innerbody were used for the pressure measurements, whereas twelve gages using acceleration compensated piezoelectric crystals arranged to differentiate between shear stress and normal pressures were used to determine skin friction. These gages were also developed at CAL.[1] The pressure drag was obtained by graphically integrating the static pressures to the throat with respect to the projected area. Similarly, the skin friction was integrated with respect to the surface area to obtain the drag due to friction in the axial direction. These two drags were then added to obtain the total internal drag. The heat loss to the inlet walls was determined from the same measurements together with Reynolds' analogy.[2] These two values plus the throat static pressure completely define the state conditions at the throat, even though the local conditions are still unknown. Throat velocity is also determined. An equivalent Mach number, throat area, and total pressure can be easily obtained.[3]

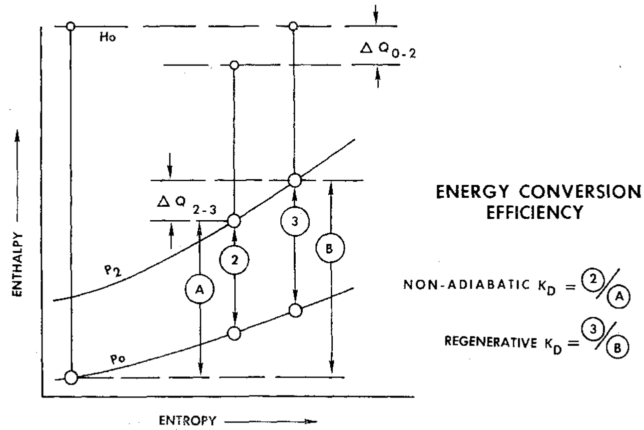
Heat transfer to the inlet walls complicates the selection of a rating parameter, which must, in any case, be somewhat arbitrary. Some of the choices available are illustrated in the Mollier chart shown in Fig. 7.

Two parameters are commonly used at present. The kinetic-energy efficiency (η_{KE}) is simply a measure of the loss of available thrust due to entropy gain. The energy conversion efficiency (K_D) accounts also for the amount of diffusion which the inlet accomplishes. If the heat transferred through the inlet walls (ΔQ_{0-2}) is simply thrown away, then the corresponding kinetic-energy efficiency is that labeled nonadiabatic. This method would be quite impractical in applying adiabatic wall or low-temperature model data to



a)

Fig. 7a Inlet performance parameters.



b)

Fig. 7b Inlet performance parameters.

flight inlets. One approximation to the actual flight case is where the heat is regeneratively returned to the airstream at constant pressure (ΔQ_{2-3}). This method also provides a good comparison with adiabatic wall and low-temperature performance. Actually, any of the foregoing definitions may be used for inlet rating if the comparisons are consistent. The mixing of definitions in comparing different inlets in different facilities can easily lead to misinterpretations.

Supplementary Heating Investigations

As Mach numbers increase, so does the number of parameters that are required for inlet performance simulation and the difficulties in obtaining meaningful data. Added to the basic low-speed Mach and Reynolds number simulation are, first, temperature and pressure, then heat transfer, skin friction, wall temperature, and real gas. It is not always possible to separate either the occurrence or the effects of these various parameters, and it has been shown that all of them exert first-order influences on inlet performance at high Mach numbers.

Although a great deal of useful information can be, and still needs to be, obtained at moderate stagnation conditions and with near-perfect testing gases such as nitrogen, there is developing an increasing need for air facilities with very high temperature and pressure capabilities. Conventional wind tunnels, with temperature limits of 3000°–4000°R and low supply pressures, become inadequate for this purpose above about Mach 6. More advanced steady flow facilities, such as magnetogasdynamics accelerators, are both costly and in the early development stages. The pulse facility, which provides relatively low-cost capabilities throughout the hypersonic and hypervelocity regime, lends itself well to such extreme-environment development. Progressively higher stagnation conditions can be obtained by simply adding more energy to the arc or driver gas. Problems such as nozzle erosion and model heating are relieved by the short running times.

In the hotshot, however, the additional concentration of large amounts of energy accentuates such problems as particle contamination, safety, and complexity of capacitor storage. In addition, facility costs would increase significantly. It would be advantageous, then, to have a supplementary heating source independent of the capacitor storage. The exothermic decomposition of nitrous oxide appears to have great potential as such a heat supplement. A stable compound at room temperature, when heated, decomposes to nitrogen and oxygen and releases large amounts of energy. If proper amounts of nitrogen and oxygen are added to the nitrous oxide in the load mixture, the resulting gas will very closely approximate air. The cost and danger of this technique would both be negligible.

The decomposition of nitrous oxide has been extensively investigated, but the actual process has remained somewhat

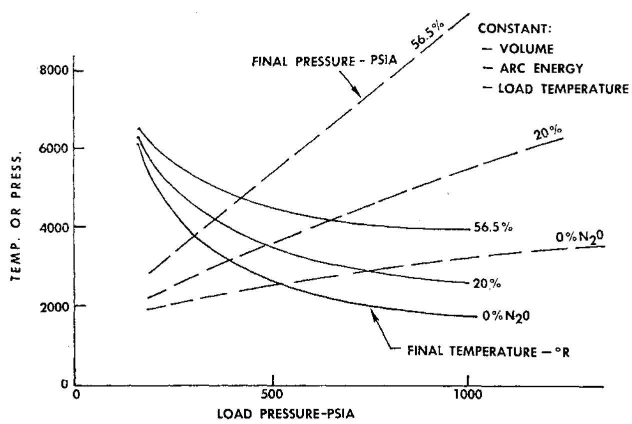


Fig. 8 Final state conditions.

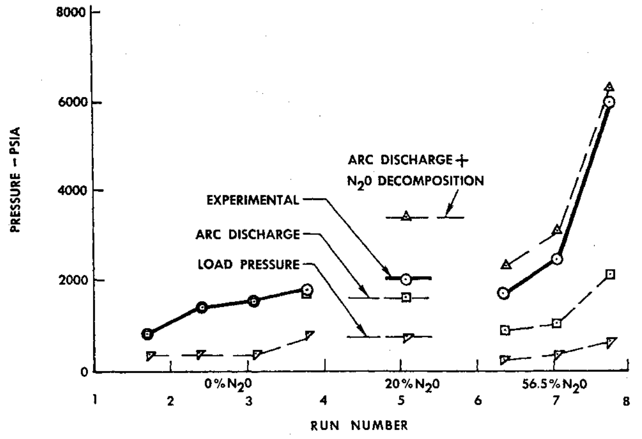


Fig. 9 TMC hotshot performance.

of a mystery. Moreover, attempts to utilize the gas as a heat source in steady-state facilities have had only limited success.[4] From these experiments, however, pertinent conclusions may be reached. The decomposition rate is extremely sensitive to temperature, approximately doubling for every 50° above 1800°R. At 2600°R decomposition occurs in much less than 1 msec.[5] The degree of completion varies directly with load pressure and inversely with foreign gas diffusion.[6] In such cases, nitrogen dioxide is formed as one of the products. This is undesirable both as a heat loss and as a contaminant. In a hotshot arc chamber, the gas in the vicinity of the arc will reach very high temperatures, and the nearly instantaneous nitrous oxide decomposition will produce additional energy. At the same time, heat transfer to the surrounding cold gas will commence. If the reaction propagates at a faster rate than the temperature dispersion, then a complete, nearly-instantaneous reaction should result. If the reverse happens, the reaction will be quenched.

Tests were performed in The Marquardt Corporation (TMC) Hotshot facility[7] using a 7000-psi arc chamber and a Mach 7 nozzle. An arc heat input of 482,000 joules was available. When chamber volume, arc efficiency, initial state conditions, and initial gas composition are known, then the final state conditions can be predicted for a complete reaction. Such a prediction is presented in Fig. 8. Three initial gas mixtures are presented: 78% N_2–22% O_2; 20% N_2O–66% N_2–14% O_2; and 56.5% N_2O–43.5% N_2. Percentages are by volume. In each case, complete decomposition would result in a 78% N_2–22% O_2 mixture. It is seen that, for this particular case, the use of nitrous oxide could simultaneously double the temperature and triple the pressure.

Fast-response thermocouples were installed but proved to be ineffective. With pressure instrumentation alone it is not possible to determine with certainty the final temperature and gas composition. However, if the arc efficiency is known, then any pressure lower than that predicted is indicative of incomplete decomposition or formation of contaminants such as NO_2 and NO. The comparison of measured pressures with predicted values is therefore valid as a performance measurement. Figure 9 presents such a measurement. An arc efficiency of 60% was established from the first four runs where no nitrous oxide was used. It is seen that in three runs using nitrous oxide the pressure levels were well below the predicted, but that a fourth run was very close to its ideal value. The reason for this is seen in Fig. 10, in which the ratio of the measured pressure rise to the theoretical pressure rise is plotted against the initial nitrous oxide partial pressure. The pronounced effects of pressure and dilution are evident.

Even when the nitrous oxide did not fully decompose into nitrogen and oxygen, the reaction was still nearly instan-

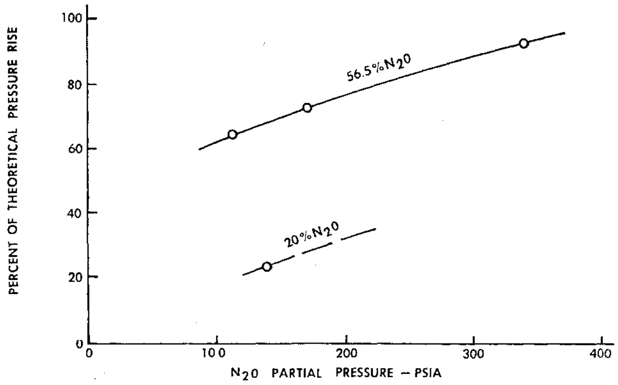


Fig. 10 Effect of pressure and dilution.

taneous. Figure 11 presents unfiltered pressure traces for two runs, one with and one without nitrous oxide. The nitrous oxide run achieved only about 70% of its theoretical pressure rise. Although high-frequency oscillations masked much of the process, it appears that maximum pressure levels were reached 7 and 4 msec, respectively, after arc discharge. The difference could be attributed to the difference in pressure levels as well as to decomposition time. Although the oscillations were excessive, they did not appear to seriously affect downstream pressures.

Even though no complete reaction was actually obtained before mechanical failures ended the test, the data indicate that a complete reaction is possible with increases in load pressure or nitrous oxide concentration. The reactions obtained showed large pressure increases over arc heating alone, and up to 92% of the theoretical pressure rise was achieved.

Another promising heat supplement is the use of small amounts of hydrogen addition to the nitrous oxide-nitrogen mixture. The resulting water vapor would be considered a contaminant, but it appears that large pressure gains can be realized with hydrogen quantities small enough to have no serious effects on the gas properties. In Fig. 12 the theoretical pressure level for the hydrogen addition required for 2% water vapor by volume in the final mixture is compared with that of the two previous cases for a specific chamber volume and arc heat input. A constant final temperature is maintained. The hydrogen contributes two gains. It adds its own considerable heat release to the mixture and, by combining with free oxygen, it increases slightly the allowable concentration of nitrous oxide. Both of these factors would also tend to assist the decomposition. Also plotted in Fig. 12 is the pressure required for a typical flight Reynolds number simulation. To date, this application has not been experimentally investigated, although future work is anticipated.

Chemical heat addition is considered to have its greatest value in the hypersonic Mach number range ($5 < M < 10$). In the hypervelocity regime ($M > 10$) the energy inputs required for temperature and pressure simulation are large in comparison to those available from chemical heating. This limitation, combined with the previously mentioned high-energy problems associated with hotshots, tends to make shock tunnels more attractive at the hypervelocity Mach numbers.

High-Temperature Test Considerations

With real gas conditions now available in pulse facilities for inlet testing, more sophisticated model design, instrumentation, and performance evaluation techniques must be developed. In addition to the friction and heat-transfer measurements previously mentioned, the internal flow must be analyzed and measured in terms such as wall temperature, bleed, boundary-layer thickness, flow distortion, and dissociation. As a beginning, a model has been designed and fabricated by TMC for flight condition evaluation in the hotshot. The main feature of this model is the inclusion of spike and cowl resistance heaters that are intended to uniformly heat the model walls to temperatures up to 2000°R. This is close to the maximum nonablating skin temperatures found on flight vehicles. Complete temperature simulation thus can be achieved for both model and airstream. By varying both the wall and stagnation temperatures, the effects of temperature ratio and real gas can be extensively investigated and cooling rates optimized. Tradeoffs between bleed and cooling can also be established.

The model described is equipped with pressure instrumentation only and thus is limited to gross separation and performance measurements. Fast-response temperature-sensing equipment would be of great value in both the arc chamber and model. Friction gages and pitot probes would also yield useful information.

At temperatures over 5000°R, gas properties must be closely watched. For example, at 9000°R, the mixture in the arc chamber can include 13% dissociated oxygen and 11% nitric oxide.[8] Careful nozzle design can recombine the oxygen, but the nitric oxide will remain frozen. This will have small effects on molecular weight and specific heat, but heat transfer and other properties may be influenced.

Conclusion

Tests in both a hotshot and shock tunnel have proved that valid inlet data can be obtained in pulse facilities. No moving parts are required to start an internal contraction inlet, and the equivalent of an exit throttle traverse can be obtained with one run. Performance agreement was obtained with wind-tunnel data. Time-dependent internal flow adjustments were observed during a number of runs. These ad-

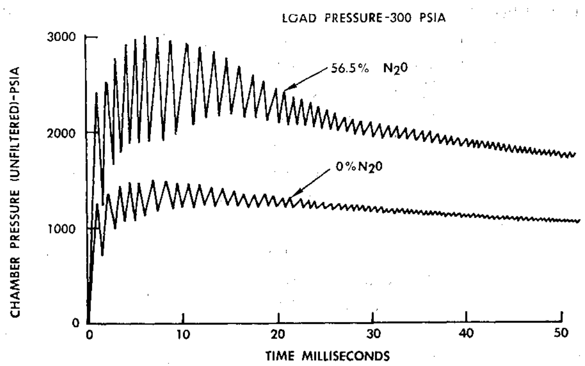


Fig. 11 Nitrous oxide decomposition rate.

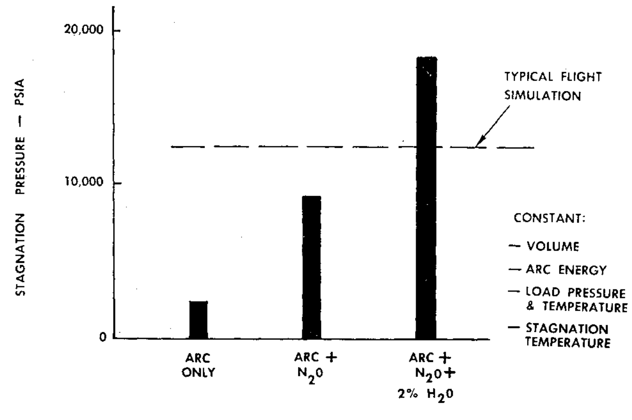


Fig. 12 Effect of chemical heat addition.

justments on occasion critically affected performance and hence require documentation.

Static pressure and skin-friction measurements were used to determine inlet performance at hypervelocity Mach numbers. This is believed to be more accurate than direct methods. The regenerative kinetic-energy efficiency is defined and proposed as a fair rating parameter for nonstagnating inlets with heat transfer.

Tests were performed in a hotshot using nitrous oxide decomposition to supplement the electrical arc heating. A decomposition of 92% was achieved, resulting both in a chamber pressure three times that obtainable by arc heating alone and in a gas mixture closely approximating air. The reaction was nearly instantaneous, and the degree of decomposition was found to vary directly with load pressure and inversely with percentage of diluent nitrogen. Use of small amounts of hydrogen is suggested as an additional heat supplement.

The effects of wall cooling and real gas are important to flight operation. A model is presented which contains internal heaters to provide precise flight-temperature simulation. Further advances in instrumentation and model techniques are required. At high temperatures, nitric oxide contamination is unavoidable in stagnating facilities, and nozzles must be designed for recombination.

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