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Resonance Tube Hazards in Oxygen Systems

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RESONANCE TUBE HAZARDS IN OXYGEN SYSTEMS*

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ABSTRACT

An experimental and analytical program was carried out at the NASA Lewis Research Center, Cleveland, Ohio, under the sponsorship of the Aerospace Safety Research and Data Institute to determine whether fluid dynamic oscillations could create a hazard in gaseous oxygen flow systems. The particular fluid dynamic oscillation studied was the resonance tube phenomena as it was excited in a tee-shaped configuration characteristic of configurations found in many industrial high pressure gas flow systems. The types of hazards that could be caused by the oscillations were direct heating and ignition of the piping system by the gas, the greatly augmented heating that could occur if inert contaminants were present, and the ignition of metallic contaminants. Asbestos was used as the inert contaminant; titanium, aluminum, magnesium and steel were chosen as ignitable metallic contaminants. The oscillations in the tee-shaped configuration were compared to oscillations driven by choked convergent nozzles and were found to differ markedly. Temperatures generated at the end or base of the resonance tube exceeded 1089 K for both gaseous oxygen and nitrogen and reached 1645 K when asbestos was added. Aluminum in both powder and fiber form was readily ignited within the resonance tube when the supply pressures were less than 8270 kPa whereas at higher supply pressures the mixture exploded with enough violence to destroy the apparatus in less than 10 sec. In addition to aluminum, magnesium, and titanium, samples of

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400 series stainless steels were also ignited within the resonance tube. The ignition occurred within a few seconds after the oxygen flow began indicating that, if resonance were induced by the proper pressure, flow and geometries due to failure of a component in a high pressure oxygen system or by an abnormal startup or shutdown sequence, the potential for ignition of contaminants does exist.

INTRODUCTION

Ignition and combustion of materials in oxygen can be caused by a wide variety of means. In the case of metals such as aluminum with protective oxide coatings, in order for ignition to occur, either the metal must be finely subdivided with a surface-to-volume ratio so high that a dust cloud ignition could occur or the metal must be heated to where the oxide layer is driven off before combustion can be maintained. There were experiments performed in which a drop of molten aluminum was ignited when it was held in a stream of oxygen flowing with sufficient force to remove any oxide buildup [1-5]. In that case, the oxidation reaction was usually sufficiently energetic to produce combustion. Since the experiments indicated that igniting metals with adhesive oxide layers was so difficult, these metals might well be regarded as being suitable for a variety of oxygen systems with no ignition hazard attendant to their use.

If, however, a means of establishing a sufficiently strong oscillatory flow field in an oxygen system were found, even bulk sized quantities of metal might be heated up by friction, and since an oscillatory flow field could provide a continual relative oscillatory velocity between gas and metal in a resonant cavity, even an adhesive oxide layer might be scrubbed off rapidly enough to allow ignition of the metal.

There is a fluid dynamic phenomenon that can develop very strong oscillatory flow fields with large thermal effects called the resonance tube phenomenon [6]. It is characteristically achieved by pointing a choked underexpanded jet of gas into a cavity. For specific values of gas pressure, nozzle and cavity geometry and with careful alignment of nozzle and cavity, intense heating can occur within the cavity. It can be readily demonstrated that a wood block can be ignited with a jet of shop air operating at 800 kPa supply pressure.

Even with this phenomenon because of the care and precision required to establish this type of resonant geometry, the oscillations probably would not occur in an oxygen system. It appears, however, that a similar resonance <u>can</u> be initiated in geometries characteristic of many tubine or piping systems. The resonance has been found to occur for a wide variety of tubing sizes, pressures and for a variety of gases.

The material presented will discuss an investigation undertaken at NASA-Lewis to determine whether this phenomenon could be used to explain certain oxygen system accidents that occurred in the aerospace field. The apparatus used, the nature of the resonance, the ranges of geometry and pressures over which it was found to occur, and the resulting thermal and ignition phenomena that accompanied its appearance are the subject of this paper.

APPARATUS

In order to develop a strong fluid dynamic resonance in gaseous flow systems, a significant pressure drop over a short distance is necessary. For the systems studied, the ratio of inlet stagnation to exit pressure was varied from a low of 1.5:1 to a high exceeding 40:1. Pressure ratios of this magnitude, while not part of the original system design, might well occur during rapid venting of high pressure systems. If a tubing (or piping) configuration was established wherein gas flowed from a tube into a larger tube, at right angles to it, and opposite the smaller tube there was any sort of cavity, the resonance was easily excited. A typical configuration is shown in Fig. 1. The resonance tube shown need not be as long for the oscillations to be developed. Oscillations were detected for cavity length of 0.0025 m. The presence of the resonance was indicated by the intense high pitched noise that was generated together with the rapid heating of the closed ended resonance tube. The resonance tube part of the apparatus need not be a cylindrical tube. As a matter of fact, substantially higher thermal effects could be initiated if the tube were irregular or rough. A capped-off tee or a valve with complex internal geometry might well provide the appropriate geometry - which is a cavity directly opposite from the inlet tube. Before selecting the apparatus that was used for the bulk of the investigation, a wide variety of inlet tubes, exit tubes, and resonant cavity tubes were tried and all appeared to produce resonance. Resonance was readily established in such mundane devices as reducing tees.

The typical tee-configuration resonance apparatus used for this study, shown in Fig. 1. was fabricated from type 304 stainless steel pipe with a nominal 0.0254 m inside diameter (ID). One end was closed off by a welded stainless steel cap with the interior surfaces ground flat. Two fittings were installed diametrically opposite each other and welded in place. These fittings enabled tubing to be attached to the pipe to serve as inlet and resonance tubes. Both the inlet and resonance tubes were fabricated from 0.007 m ID stainless steel tubing. For visual observation of contamiant behavior during a test, a quartz tube with an outside diameter (OD) of 0.006 m and a wall thickness of 0.001 m was used. These tubes, fused shut at one end, were attached to the resonance tee by a 0.76 m long steel tube of the same inside diameter with a gasket seal at the quartz-steel interface. The overall length of the resonance tube was 0.15 m for both the all-steel and the quartz-steel composite tubes.

The flow system is shown schematically in Fig. 2. It consisted of high-pressure gaseous nitrogen and oxygen sources, stainless steel flow lines, pressure controllers, fire valves and an exit-flow control valve. Static pressure transducers, designated by the symbol P, and Chromel-Alumel thermocouples, designated by the symbol T, were attached to the flow system at the points shown in Fig 2. The pressure and temperature of the flows entering the apparatus could be continuously monitored and recorded on an oscillograph. In addition, a Venturi type of flow meter was installed to measure the gas flow rate. The combined flow and pressure measurements allowed the calculation of the inlet stagnation and static pressures. Piezoelectric types of pressure transducers were used to measure mean and transient pressures at the base of the all-steel resonance tube. Temperature measurements at the base of the quartz tube were obtained using a platinum-platinum/13 percent rhodium butt welded thermocouple junction, which had response times of 1-20 msec. In order to measure the temperature profile within the quartz tube, three sets of fine thermocouple wires were installed at different axial positions.

RESULT AND DISCUSSION

Classical Resonance/Broad-Band Resonance

The all-metal resonance tee configuration was evaluated both with the nozzle insert at the end of the inlet tube and without it. With the geometry fixed, the objective was to determine the stability of the system as the ratio of the inlet stagnation pressure to the pressure within the exit flow tube was varied. This variation was obtained by adjusting the exit flow valve shown in Fig. 2 while maintaining constant inlet stagnation pressure. The results are shown in Fig. 3. Only gaseous nitrogen was used for this particular set of data. The temperature measured at the base of the resonance tube was obtained as a function of time on a recording oscillograph. Steady-state temperatures were reached after varying periods of time, generally less than 30 seconds. The steady-state data for both types of configurations are superimposed on the same plot. The line labeled "typical variation" was obtained with the nozzle insert and the other obtained with the constant diameter inlet pipe. The variation in base heating with pressure ratio is characteristic of the classical resonance tube phenomena and reflects the effect of tuning the system so as to operate at one of the peaks in the base temperature curve which corresponds to the strongest oscillations within the resonance tube. It is generally recognized that the resonant oscillations involve multiple shock waves that continually heat the gas that is trapped at the base of the tube.

The curve representing the present study, obtained without a nozzle, is obviously far less sensitive to any tuning process and from a pressure ratio of 10:1 on up to the facility maximum stayed relatively flat in heating. This type of oscillation can be termed a resonance tube oscillation in industrial tubing configuration or industrial resonance mode, for short.

Pressure Oscillations

In order to characterize the oscillations within the resonance tube, a high frequency pressure transducer was flush mounted to the base of the all-metal resonance tube. Since the study was restricted to gas dynamic measurements, the bulk of the tests made were with gaseous nitrogen. Spot checks with gaseous oxygen indicated similar results. The output of the high frequency pressure transducer was recorded onto magnetic tape for analysis. By playing the tape back into an oscilloscope equipped with a camera, a record of the oscillatory wave shape could be obtained. A typical result is shown in Fig. 4. The inlet stagnation pressure was 3450 kPa. The peak to peak amplitude of the oscillations was of the order of 1/4 of the inlet stagnation pressure with a frequency in excess of 3300 Hz. The nature of the wave shape is indicative of shock waves generated at or near the inlet to the resonance tube that travel down it, reflect off the closed end and travel back out of the tube. Clearly, any material at the base of the tube would undergo shock pressure and thermal effects with very high repetition rates. The tests were conducted with all-metal resonance tubes and no effort was made to allow the tubes to reach steady-state temperature due to the sensitivity of the high frequency transducers to high temperature. No attempt was made to ignite the steel tube with oxygen.

Modeling of the Heating in a Resonance Tube

In order to determine the important physical mechanisms that occur within the resonance tube, an unsteady lumped parameter model was formulated. The model was based on shock type heating of the gas, frictional heating, convective heat transfer to the walls and the base of the tube by the gas, and a reduction of the shock strength as the temperature increased. The equations were reformulated as dimensionless parameters which were numerically solved for a range of input oxygen conditions. The result of a typical calculation is shown on Fig. 5. The analytical model is shown by the solid lines and experimental data for the same conditions is shown by the open symbols. While the agreement between analysis and experiment is better at lower pressures, it appears that the important mechanisms have been identified. A more detailed review of the analysis can be found in Ref. 7. The results of the analysis and experiments indicated that the heating was increased by increasing the inlet pressure, decreasing the gas molecular weight and decreasing the resonance tube thermal capacitance.

Temperature vs Inlet Pressure, Quartz-Steel Tube, Oxygen Gas

In order to observe the behavior of material within the resonance tube during operation, it was necessary to construct a tube with an optical port capable of handling the large vibrations and high temperatures and pressures attendant to the oscillations. Numerous attempts were made to incorporate quartz or fiber optic ports into metallic or refractory lined tubes but the environment proved to be too severe. It was necessary to isolate the glass/metal seal from the region of maximum temperature and pressure variation. The resultant tube was half steel and half quartz with the glass/metal seal in the middle. In order to monitor the thermal and ignition processes, it was necesary to develop thermocouples capable of withstanding the environment within the tube without sacrificing too much response time. The 0.00002 m diameter platinum-rhodium butt-welded couples used were capable of response times of from 1-20 msec. Thus the high frequency temperature oscillations that were doubtless occurring at the base of the resonance tube could not be measured. Rather some average temperature could be obtained. The quartz tubes used were 0.006 m diameter with 0.001 m wall thickness.

The variation of the temperature with time in a quartz-steel tube, using oxygen over a range of inlet pressure, is shown in Fig. 6. Only the industrial-mode resonance was considered. The temperatures were considerably higher than with the metal tubes and, after temperatures of approximately

811 K were reached, a bright glow was emitted from the quartz tube. The maximum heating rate recorded in this investigation for oxygen was 2600 K/sec. At the higher inlet pressures, the quartz tube generally failed before the temperature equilibrated.

Some of the temperatures shown are well in excess of the aluminum melting point (922 K), but far less than aluminum's published bulk ignition temperature (2311 K); thus it was expected that bulk aluminum samples could not be ignited but that dust particles might be. The parametric effect of increasing inlet pressure can be seen to increase temperature.

Effect of Fibrous Materials on Resonance-Tube Temperature with Oxygen Gas

The interaction of an industrial mode resonance tube with fibrous materials was studied by placing loose fibers within the resonance tube. According to the literature, small solder particles inserted in the classical-mode resonance tube contributed to a sharp increase in the heating rate. Before introducing the additional complication of chemical reaction, it was decided to explore the effect of inert fibers on the tube temperature. The inert material used was asbestos fibers, which were tested in both gaseous oxygen and nitrogen. The resonance apparatus used to study the effect of inert fibers was identical to that used for the thermal measurements. High-speed (100 frames/sec) color movies were used to obtain the approximate position of the fibers and to study their behavior during the heat-up period.

Typical experiments consisted of inserting various masses of asbestos fibers into the tube and turning on the flow. The asbestos consisted of 0.00007 m diameter fibers approximately 0.001 m long. The result of adding 100 mg of the material to the quartz-steel resonance tube is shown in Fig. 7. For a calibration, the transient temperature variation for the tube without fibers is shown on the same figure. The notes appended to the curve describe the conditions within the tube during the heating process.

Initially, the asbestos was compacted into an apparently solid mass that moved only slightly from the end of the tube. The temperature during this period was less than the value without asbestos. At approximately 3.5 sec, the mass disintegrated into a fine haze of particles and the temperature rose sharply with a gradient 2-3 times the initial temperature gradient of the calibration curve. The haze began to glow as the temperature exceeded 950 K. Maximum temperatures achieved were approximately 1500 K at which point some of the material appeared to fuse, perhaps with the softened quartz of the tube wall. The temperatures decreased slightly until the test stopped at 30 sec.

There were three notable results of these tests: (1) the temperature of the fiber-laden tube before the mass disintegrated was substantially lower than the calibration curve; (2) the temperature rose sharply when the fiber mass disintegrated into a fine powder; and (3) the maximum temperature achieved was approximately twice that obtained without the fiber/particulates.

Ignition Tests - Oxygen Gas

The first phase of the ignition tests was to determine what materials could be readily ignited in the resonance tube. All efforts to securely anchor or cement the samples to the base of the quartz tube were ineffective so that the materials for testing could only be evaluated by inserting them, prior to testing, into the tube. The apparatus was then reassembled and the oxygen flow was initiated. The conditions were monitored by a movie camera focused on the resonance tube. The first tests established that a variety of hydrocarbon-based oils could be ignited in a few seconds, depending on the pressures used. The ignition was indicated by bright flashes within the tube. Following these tests, small slices of transparent acrylic and polycarbonate plastics were ignited. For the metallic tests, the initial samples were titanium foils. These were also readily ignited as was expected. Following these tests, samples of magnesium and stainless steel foils were tried. In the case of magnesium and type 430 stainless steels, ignition was achieved after the pressures were increased to 3500 kPa. In the case of the 300 series stainless steels, no ignition was obtained up to the 16 MPa limit of the facility.

Following these preliminary tests, the tests with aluminum were initiated. The bulk of effort was concentrated on aluminum since the tenacious oxide coating and high quoted bulk ignition temperature would provide a critical test of the resonance tube ignition process.

Aluminum Ignition Tests - Oxygen Gas

The first phase of the ignition tests was to insert small masses of aluminum fiber of various weights into the resonance tube and turn on the flow of oxygen. The fibers used had square cross sections of 0.0001 m and were ~0.01 m long. The experimental apparatus was the same as for the inert fibers. It was found necessary to incorporate a light-sensing cell within the system to promptly turn off the oxygen flow after a bright flash had occurred. Failure to do so could result in propagation of burning metal particles into the exit flow stream. On one occasion, the burning aluminum particles ignited the stainless steel part of the resonance tube, which, in turn, ignited the major portion of the downstream piping and destroyed the exit-flow control valve.

A typical temperature-time plot resulting from this phase of the experimentation is shown in Fig. 8. The corresponding calibration curve for the resonance tube at the same inlet pressure, but with no fibers, is shown on the same plot. A shredding and then compacting of the fibers occurred during the initial rapid heating phase, followed by a suspension of motion at a temperature corresponding to the melting of the metal. During the melting process the mass became increasingly plastic and at some point disintegrated. Within 10-30 msec after disintegration, a brilliant flash was noted as the metal ignited and proceeded to burn. The combustion persisted for nearly 1 sec or until the flow was completely turned off. The brightest region of the emitted light always corresponded to that part of the tube where the metal was last seen concentrated. When aluminum samples of 30 mg or more were ignited, both the thermocouple wire and the quartz tube disintegrated, testifying to the violence of the ignition. Consequently, the only thermal evidence of ignition was the vertical line of the thermocouple output trace on the oscillograph.

Occasionally, the tube failed immediately after the sample had melted and flowed against the tube walls but before the ignition took place. The quartz fragments captured and recovered for inspection showed a thin layer of aluminum uniformly deposited on the interior of the tube walls. Although the layer of aluminum was thin relative to the size of the tube, it was quite massive in relation to those particles that had been shown to ignite at temperatures less than the aluminum oxide melting point (2311 K). Thus the sample that ignited was apparently a bulk-sized material with an unexpectedly low ignition temperature equal to the melting point of aluminum (922 K).

It is our contention that the reason for the low-temperature ignition is the high-velocity oscillatory flow within the resonance tube. This type of flow field is unique in that it provides a high relative velocity and hence a high frictional force between the gas and the particles, but it does not tend to remove the particles from the high-temperature region or decrease the relative velocity as the particles were accelerated by a steady high-velocity flow stream. The relative velocity can alter the bulk ignition limit by either continuously scrubbing the oxide off of the molten metal and exposing fresh surface to oxygen attack, or by tearing off small particles of molten aluminum that can ignite by lower-temperature dust-particle mechanisms.

For the scrubbing mechanism, the heat release that would attend each successive removal of oxide surface and replacement by fresh oxide would be shared by both the metal and the oxide layer. The heat remaining in the metal would contribute to heating the metal surface, thus increasing the oxidation rate. Under these circumstances the ignition temperature for materials that are molten in an oscillatory flow field is the surface melting point, and only the surface of the molten material would ignite.

The tearing off of small particles from a larger liquid mass has been studied in some detail as it applied to liquid droplet combustion. A criterion that has been postulated for deciding when a particular droplet will fragment is the Weber number, the ratio of the aerodynamic forces on the droplet to the surface forces that tend to keep it together. For the conditions prevailing within the resonance tube, a Weber number in excess of 400 is estimated, and thus a molten droplet of aluminum would readily break up into a larger number of potentially fine droplets. The oxide skin of the mass allowed it to retain its integrity until it was completely molten. The ignition temperature thus corresponds to the bulk melting point of the material. All of the fragmented aluminum would be expected to ignite.

Based on the observations made, the following mechanism can be postulated:

1. Shredding and compacting of the fibers combined with a frictional heating mechanism cause excess temperatures. The shredded and compacted fibers become molten and are compacted into a smaller compacted mass that rapidly oxidizes.
2. The change in size of the mass causes the frictional heating mechanism to cease, and the resonance phenomenon-perhaps inhibited by the mass suspended within the tube-heats it until the entire mass is molten.
3. At this point the aerodynamic forces are sufficient to tear apart the molten mass into fine droplets.
4. These fine droplets ignite by a small particle dust-type ignition.

At atttempt to correlate the time to ignition with the weight of the sample is shown in Fig. 9. The time from the start of the test to ignition sensing is plotted as a function of the aluminum sample weight in milligrams. The tests were conducted over a wide range of inlet oxygen pressures. The results show that higher sample weights required more time to ignite. If the mechanisms previously discussed are valid, then the effect of increased weight can be interpreted as requiring increased time to completely melt the sample.

High-Pressure Aluminum Fiber Ignition - Oxygen Gas

The next phase in the experimental program was to ignite the aluminum fibers at or near the maximum facility inlet stagnation pressure, which was in excess of 16 MPa for the apparatus used. The experimental procedures were the same as with the previous ignition tests.

Instead of a bright flash followed by a sustained burning, as in the case of lower pressures, there was an explosion that destroyed the tube and showered burning molten aluminum throughout the test cell. The tests were repeated with varying weights of aluminum fiber at pressures in excess of 8 MPa, and explosions were noted in every case. The film records of the test showed that the interior of the tube was filled, before the explosion, with a diffuse cloud of fine particles immediately after the flow was turned on. There was no compacting or apparent melting at any time during the preignition period. The high pressures had increased the aerodynamic forces within the tube to the point where the fiber was shredded into a fine powder that then ignited or exploded by a dust explosion mechanism of the type discussed previously.

The thermocouple readings for all of the fiber explosions are shown in Fig. 10. In addition to the high-pressure tests, the thermocouple output for preoxidized fibers at 7.6 MPa is shown. The preoxidized sample represents aluminum fiber preheated at 640 K in an air filled oven for 1.5 hr prior to the ignition test. The oxide layer that formed on the fibers was considerably thickened, according to photomicrographic analysis. It was anticipated that the thickened oxide layer would render the fibers much more brittle so that the high-pressure-fine-dispersion explosion sequence would take place, but at lower pressures. The test revealed that this indeed occurred.

The explosion results were surprising from two standpoints-the relatively low temperature at which ignitions occurred (on the order of 470-640 K) and the decreasing of the temperature below the calibration curve, implying no excess heating even though there were fine particles present within the tube. A possible explanation is that the particles were reduced to such a fine size that the relative velocity between their motion and the gas was reduced to very low levels due to inertial effects. The frictional heating-which was proportional to the relative velocity-might then have been reduced to a negligible amount, in which case the thermal capacitance of the particles would have caused a net reduction in the average temperature measured within the tube.

The ignition of aluminum in the resonance tube can be summarized as follows. For pressures below 8 MPa or for nonbrittle samples, the excess heating due to gas-particle friction melted the fibers and broke the melt into small fragments that could readily be ignited in the tube; for higher pressures or more brittle samples, the effect of the resonance was to fragment the fibers so finely that the particles did not contribute to excess gas-particle frictional heating. The fine particles, however, did explode at temperatures considerably lower than that expected for bulk samples and in accord with dust particle experiments (2).

Powder Ignitions

As an additional experiment, roughly spherical particles of aluminum of 0.0007 m average diameter were inserted into the resonance tube. The thermocouple outputs for these tests are shown in Fig. 11. The experiments were conducted with pressures as low as 4.6 MPa, and the results presented show the same characteristics of subcalibration temperatures, fine cloud dispersion (as seen on film), and explosions.

The powder experiments performed support previous information in the literature [2] that small particles of aluminum metal will self-ignite at relatively low temperatures. The results obtained support the concept of dust-type explosions as it applies to the resonance-tube ignition phenomenon.

CONCLUSIONS

The objective of this study was to determine whether fluid dynamic oscillations could pose a hazard for oxygen systems. The results indicated that they very definitely could. Hydrocarbon oils, plastic and metal fibers and powder were ignited by resonance-tube oscillations. The fiber ignition mechanism involved the following sequence of steps: (1) shredding and compacting of the material with frictional heating; (2) melting, oxidizing, and disintegration of the material after a melting time that varied with sample size and pressure; and (3) ignition and combustion of the material.

At higher pressures, or with powders or embrittled samples, the fine particulate materials exploded within the tube at temperatures considerably below the melting temperature. The configuration used was typical of piping configurations found in high pressure gas systems. Although all of the ignitions were recorded in quartz-steel composite tubes that increased the temperature due to their insulating capability, comparable effects could be anticipated in all-metal configurations at higher gas-supply pressures, as well as in well-insulated systems. The amount of heating increases as the molecular weight of the gas decreases, the pressure increases, and the tube material thermal capacitance decreases.

The ignition of particulates can take place in a few seconds, which implies that the resonance-tube pressure and velocity requirements need only be existent for short periods for an ignition problem to arise. Thus it would be possible for a high-pressure gas system to be driven into resonance by the failure of a component that rapidly decreased the pressure within the system in a short period of time, causing high velocities and thus short-term resonant conditions.

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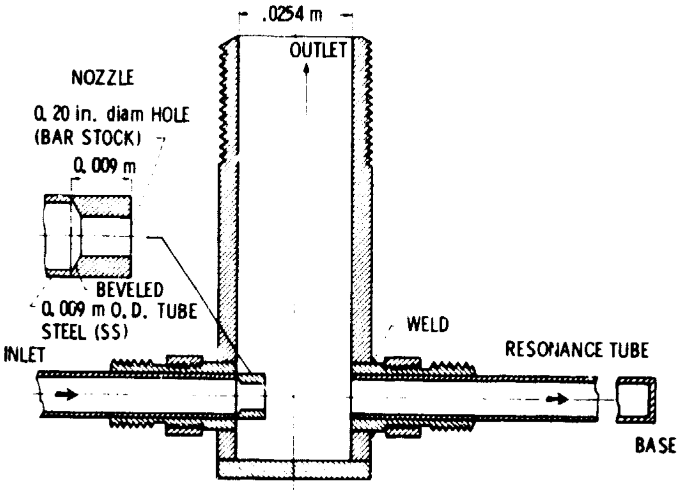
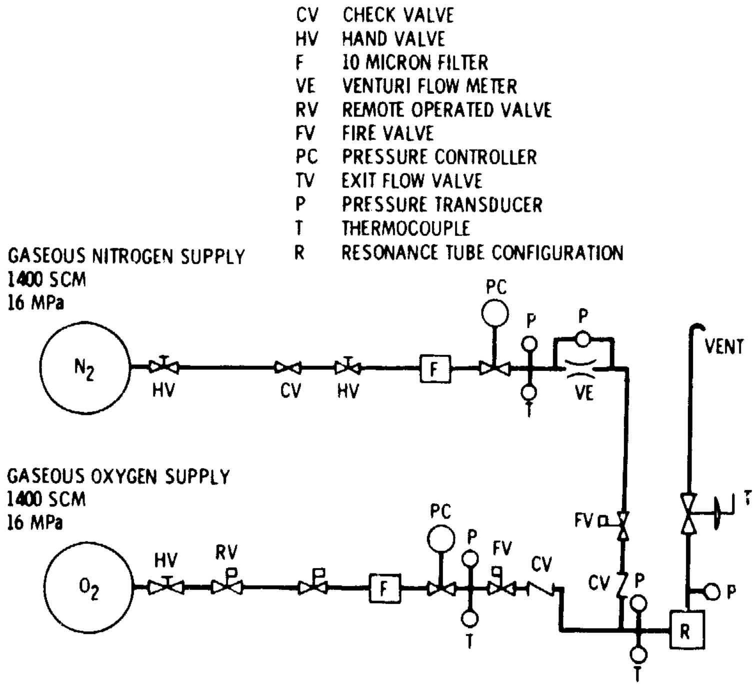


Figure 1. - Resonance tee used in this investigation.



CV	CHECK VALVE
HV	HAND VALVE
F	10 MICRON FILTER
VE	VENTURI FLOW METER
RV	REMOTE OPERATED VALVE
FV	FIRE VALVE
PC	PRESSURE CONTROLLER
TV	EXIT FLOW VALVE
P	PRESSURE TRANSDUCER
T	THERMOCOUPLE
R	RESONANCE TUBE CONFIGURATION

Figure 2. - Schematic of flow system.

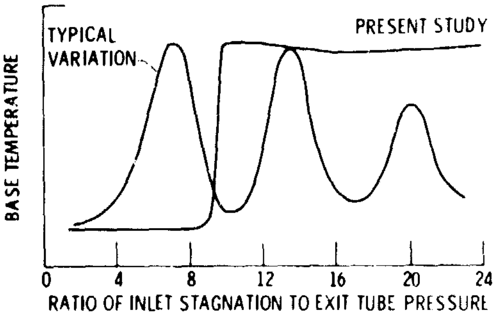


Figure 3. - Steady state base temperature vs the ratio of inlet stagnation to exit tube pressures.

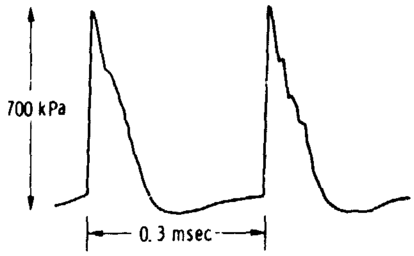


Figure 4. - Typical wave shape for industrial resonance mode base pressure oscillations.

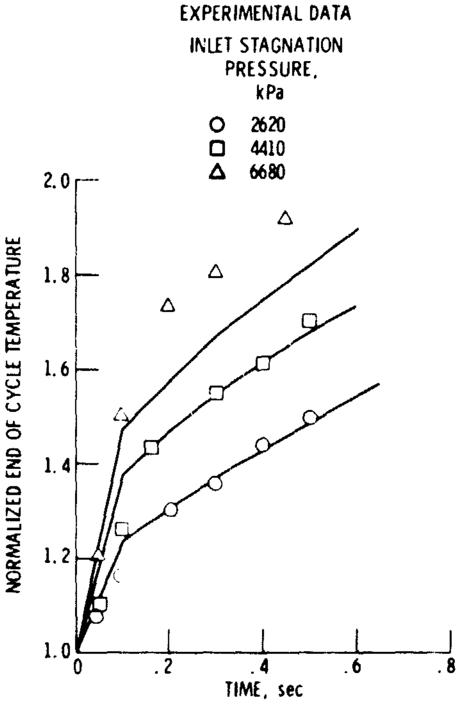


Figure 5. - Comparison of industrial mode model calculations with experimental data. Steel-quartz tube, gaseous oxygen.

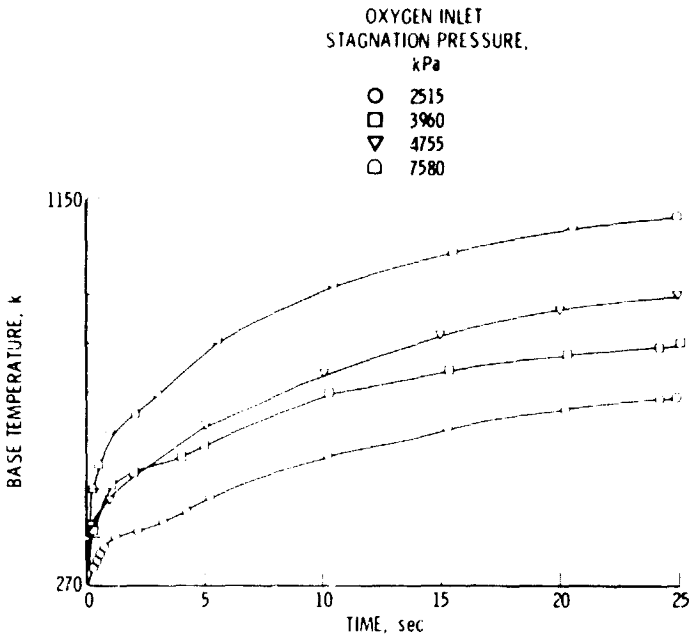


Figure 6. - Typical variation of base temperature with time. Quartz-steel resonance tube, industrial mode.

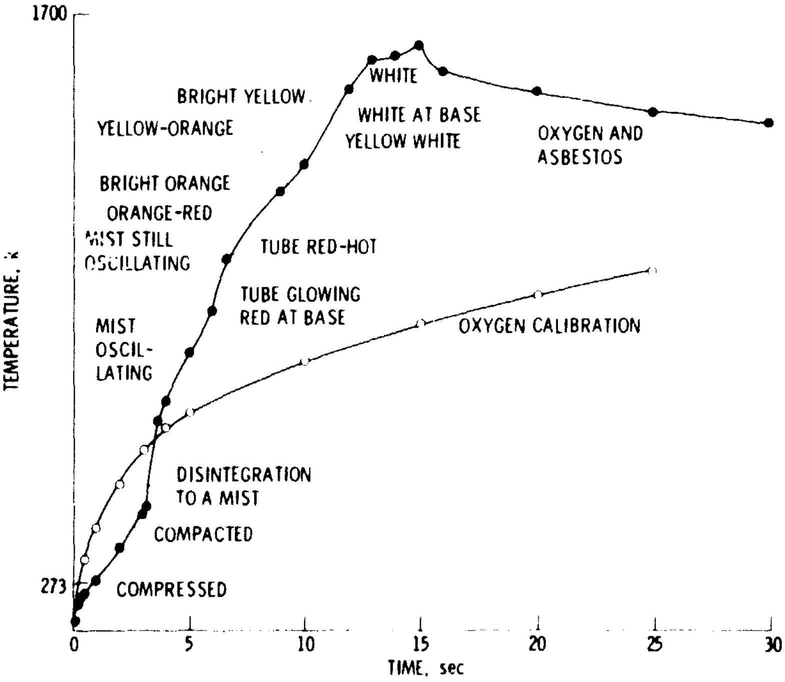


Figure 7. - The effect of asbestos particle addition on the temperature transient, industrial mode, quartz/steel tube, gaseous oxygen, inlet stagnation pressure = 7000 kPa, 100 mg asbestos.

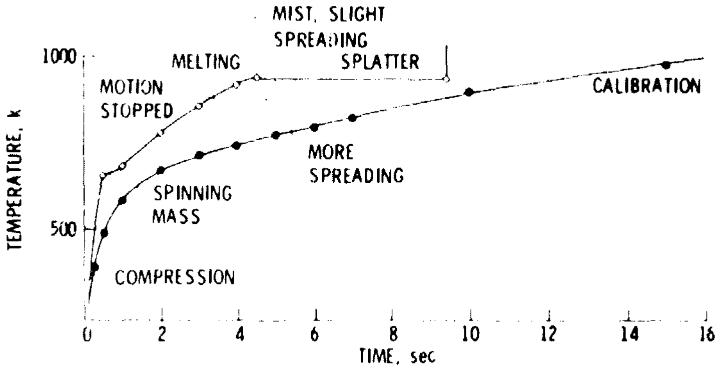


Figure 8. - Ignition of aluminum fiber. Inlet stagnation pressure = 7580 kPa, 30 mg fiber, ignition at 9.45 sec, gaseous oxygen.

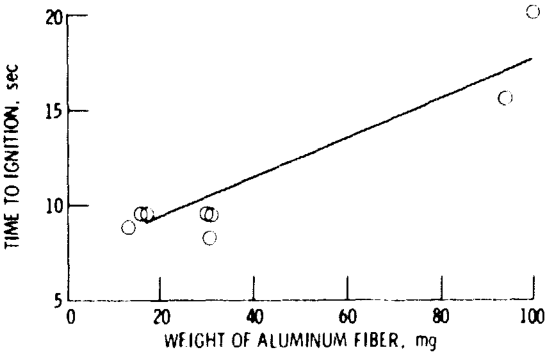


Figure 9. - Ignition time as a function of weight of aluminum fiber.

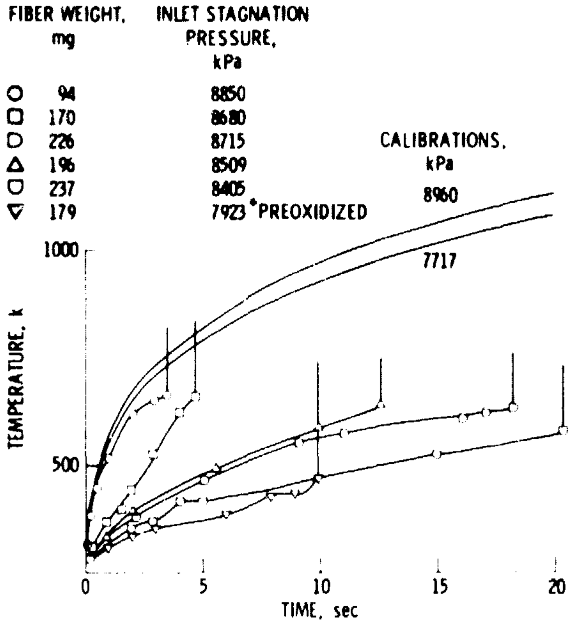


Figure 10. - Explosion of aluminum fiber in gaseous oxygen.

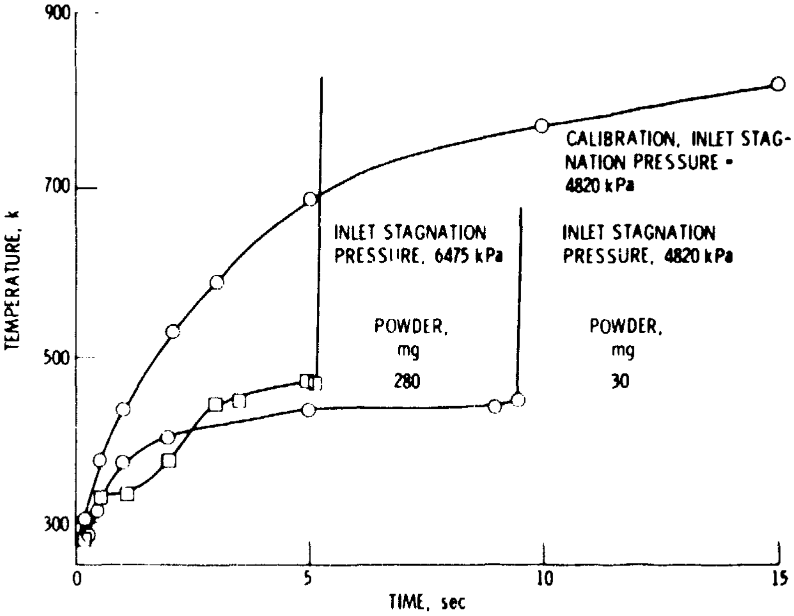


Figure 11. - Explosion of aluminum powder. Average particle diameter - 44 microns. In gaseous oxygen.