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A GRAPHITE RESISTANCE HEATER FOR A HYPERSONIC WIND TUNNEL USING NITROGEN: PART I. DESCRIPTION OF TUNNEL AND HEATER

R. P. SHREEVE,† W. T. LORD,‡ S. J. BOERSEN§ and S. M. BOGDONOFF
Gas Dynamics Laboratory, Princeton University, Princeton, New Jersey, U.S.A.

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Abstract—A heater system has been developed for a hypersonic wind tunnel which uses nitrogen as the test gas, and operates continuously at Mach numbers up to 20. The system uses a small electrically heated graphite element containing a spiral gas passage.

A small pilot hypersonic nitrogen tunnel has been used in the development of the heater system. The tunnel is designed to operate ultimately at a gas stagnation pressure of 10 000 lbf/in^2, but the work described here refers to operation at up to 1000 lbf/in^2 stagnation pressure. This paper is concerned principally with the development of the heater system, and not with the establishment of high Mach number flow in the test section (for which purpose a second hypersonic nitrogen tunnel is being used).

The stagnation temperature required to avoid condensation of the nitrogen in the test section at a Mach number of 20 is about 5000°R. The major problems encountered in achieving such a temperature, which is below that at which nitrogen begins to dissociate and so starts to react with graphite, have been caused by chemical reactions involving substances other than pure nitrogen and pure graphite. The purity of the gas supply, the cleanliness of the equipment and the grade of graphite are of the utmost importance. A thin impermeable coating of pyrolytic graphite over the outside of the heater element has been found to prevent the formation of holes in the outer wall, which occurred with uncoated elements. Such coated elements have regularly been used to provide steady gas temperatures up to 5000°R at 1000 lbf/in^2 pressure. (The results are presented in detail in Part II.)

Extending operation of the heating system to higher pressures is expected to present only minor problems. Gases other than nitrogen have been successfully used with the present heater and it is further suggested that experience gained with the described system will have application in the design of a similar heater for air as suitable non-oxidizing materials become available.

NOMENCLATURE

c_{p0},	value at room temperature T_0 of specific heat of gas at constant pressure, 261·7 J/lb degR for nitrogen at 530°R;
i,	current (A);
m,	mass flow of gas (lb/s);
m_0,	cold mass flow of gas (lb/s);
p_t,	total pressure of gas (lb/in^2);
p_{t_0},	total pressure of gas in cold flow (lb/in^2);
r_0,	cold resistance of element (Ω);
A^*,	area of nozzle throat (in^2);
A^*_0,	area of nozzle throat in cold flow (in^2);
R,	gas constant for unit mass of gas;
T_0,	room temperature, values of T_t in the cold flow (degR);
T_t,	total (stagnation) temperature of gas (degR).

Greek symbols

γ,	ratio of specific heat at constant pressure to specific heat at constant volume for a gas;
η,	efficiency of heater system;
σ,	current parameter, defined as $i^2r_0/m_0c_{p_0}T_0$;
τ,	total temperature parameter, defined as $(T_t - T_0)/T_0$;
ω_0,	pressure drop parameter, defined as the cold pressure drop in the heater passage divided by p_t;
Γ,	non-dimensional factor.

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† Now at Boeing Scientific Research Laboratories, Seattle, Washington, U.S.A.

‡ On leave during 1959–60 from the Royal Aircraft Establishment, Farnborough, Hampshire, England.

§ Now at the National Aero- and Astronautical-Research Laboratory, Amsterdam, The Netherlands.

1. INTRODUCTION

IN RECENT years, the interest in hypersonic flight has stimulated the development of experimental tools which can stimulate conditions of ultra high speed flight (Mach numbers of the order of 20) in the laboratory. Several new types of test facilities have been evolved [1, 2]. Such facilities as the "hot-shot" tunnel, the shock tunnel, and the arc or plasma tunnel have been designed to provide the high enthalpies, and hence many of the real gas effects, which are experienced in hypersonic flight. However, the flows produced in these facilities are very complex (there are basic questions of flow composition and steadiness) and measurements are difficult to make because of the extremely short running times (of the order of milliseconds) in the case of the "hot-shot" and shock tunnels or because of the high heat transfer rates in such equipment as arc tunnels. The short running times preclude many of the types of test which are carried out in conventional wind tunnels. The most serious restriction, however, is the lack of detailed information on the composition of the gas in the test section.

A somewhat different approach to the experimental study of hypersonic flows is being followed by the Gas Dynamics Laboratory of Princeton University. The method is to try to isolate the fundamental fluid mechanical effects at high Mach numbers by avoiding the complexities of high temperature effects, which, as yet, are not completely understood. This can be done using conventional wind tunnel techniques if the test gas which is used behaves as a thermally perfect gas throughout. The only real gas effects involved are those due to vibrational excitation. The problem then becomes one of designing a high Mach number wind tunnel to operate at conditions where there is neither condensation of the test gas during expansion in the nozzle nor dissociation in the stagnation chamber. These considerations determine respectively the lower and upper limits to the stagnation temperature which must prevail in any given gas operating at a desired stagnation pressure. The case when these limits are equal defines a maximum Mach number at which a hypersonic wind tunnel of this type can operate.

If air is the test gas, some form of heater is necessary to avoid condensation in flows at Mach numbers greater than about 5, and a stagnation temperature of the order of 5000°R is required to provide a Mach number of 20. If helium, which has a very low condensation temperature, is used as the test gas, flows at Mach numbers greater than 25 are obtainable without using a heater. A helium hypersonic tunnel, such as that in operation at the Gas Dynamics Laboratory of Princeton University [3], provides a quite simple apparatus for the experimental study of hypersonic flows. Its operation is directly comparable to that of a conventional supersonic blow-down wind tunnel, running times are long and all of the usual wind tunnel measurements can be made with ease. However, since helium is a monatomic gas with a ratio of specific heats γ equal to 1·67, whereas air behaves more like a diatomic gas with γ equal to 1·4, the results from tests using helium are not directly applicable to the simulation of flight in air. Although it has been proposed that the results of tests using helium may be used, in some instances, to predict the results which would be obtained using air [4], the theoretical understanding of hypersonic flows is not adequate, at the moment, to justify any widespread conversion, particularly for complicated shapes. (For simple shapes, the helium tunnel provides a direct way to check theories in which γ can be explicitly included.) In view of these considerations, there is a need for a hypersonic wind tunnel which uses air, or a similar diatomic gas, and which is capable of continuous operation in the range of Mach numbers from 10 to 20.

Mach numbers up to about 14 have been obtained in wind tunnels using various heating systems such as wire electrical heaters [5] and pebble bed heaters [6]. For higher Mach numbers, requiring gas stagnation temperatures in excess of 3000°R, there exists the difficulty of finding heater materials which will withstand hot oxidizing atmospheres. The solution proposed in 1957 by Hammitt†, was to avoid the oxidation problem by using a gas which has properties

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† Dr. Hammitt, now at Space Technology Laboratories Inc., initiated the present investigations, carried out the original experiments and continued to be associated with the work until June 1960.

similar to those of air and yet is inert to some particular heater material in the relevant temperature range. Nitrogen and graphite appeared to constitute such a desirable combination of test gas and heater material [7, 8, 9]. No chemical reaction is predicted to occur between nitrogen and graphite until the nitrogen becomes dissociated [7, 9]. Significant dissociation of nitrogen begins to occur at 8000°R at atmospheric pressure and at correspondingly higher temperatures at higher pressures. Since graphite sublimes at about 7200°R, the theoretical limit of the combination is set by the sublimation of the heater material. Consequently it was thought possible to use a graphite heater with nitrogen in a hypersonic wind tunnel designed to operate at a Mach number of 20, for which the test gas must be heated to about 5000°R in order to avoid condensation.

Experiments began in 1958 directed towards the development of a simple graphite resistance heater which would heat a continuous flow of nitrogen. The method adopted was to house a resistance heating element inside a pressure vessel (which resembled the stagnation chamber of a conventional blow-down wind tunnel) in such a way that nitrogen supplied to the surrounding space passed through a heat transfer passage in the element before entering the wind tunnel nozzle. A small pilot hypersonic nitrogen tunnel has been used in the development of the heater system. The tunnel is designed to operate ultimately at a stagnation pressure of 10 000 lbf/in^2, for which the required stagnation temperature for a Mach number of 20 would be about 5000°R, but for the study reported herein the operating pressure has been limited to 1000 lbf/in^2 for which the required stagnation pressure is about 4500°R. The emphasis of the work in the pilot hypersonic nitrogen tunnel has been placed on heater development and only the most preliminary investigations of the flow in the nozzle have been made. (A second hypersonic nitrogen tunnel is being used for detailed flow investigations.) It is realised that, although departures from thermodynamic equilibrium have been neglected in the estimates of required stagnation temperature, the effects of vibrational relaxation are not negligible [10] and must be considered when investigating the flow in the nozzle.

The experimental development program has involved the testing of several different element geometries, and several different grades of graphite have been used. Early in the investigations, concentration was put on a simple rod-like element containing a single spiral heat transfer passage which was made from a very dense grade of graphite. Steady and repeatable operation of the system (at 1000 lbf/in^2 pressure) at gas temperatures suitable for a test section Mach number of about 20 has been achieved following the use of some of the most recently developed grades of graphite, including pyrolytic graphite. The pilot nitrogen tunnel is being used to develop the heater system for operation at higher pressures.

The purpose of the present paper is to report the investigations up to the point at which the initial aim, of providing a working heater system for a nitrogen tunnel designed to operate at a Mach number of 20, was achieved. A description of the tunnel and heater is given in this Part I. (More details of the early experimental development of the heater element are to be found elsewhere [11].) An analysis of the experimental results is given separately in Part II of this paper [12]. Here the design of a hypersonic nitrogen tunnel is considered and the present equipment is described in Section 2. In Section 3 the design of the heater element itself is discussed and some account is given of the development. Some particular results from heater performance tests are presented in Section 4. The characteristics, difficulties and future possibilities of this type of heater are discussed in Section 5.

2. THE PILOT HYPERSONIC NITROGEN TUNNEL

Detailed thermodynamic properties of nitrogen are tabulated for pressures up to 100 atm and for temperatures up to 5400°R [13]. These tables are sufficient for the purposes of the investigation reported herein, but more information will be required later for operation at higher pressures [14].

An examination of the tables confirms that, for the combinations of pressures and temperatures to be expected in the gas flow, it is reasonable to consider nitrogen as a perfect gas with variable specific heats. Moreover, the variation of the ratio of the specific heats of nitrogen with temperature in the appropriate temperature range is very nearly the same as that for air [15], and so it is reasonable to use the extensive tables already available for air as a thermally perfect gas to give the isentropic flow properties of nitrogen. This procedure has been followed wherever permissible in the calculations performed for this work. The values of total (stagnation) temperature which correspond to saturation of nitrogen in the test section of a wind tunnel at various Mach numbers and stagnation pressures (calculated by a method ignoring the thermal imperfections of the gas near to condensation), are shown in Fig. 1.

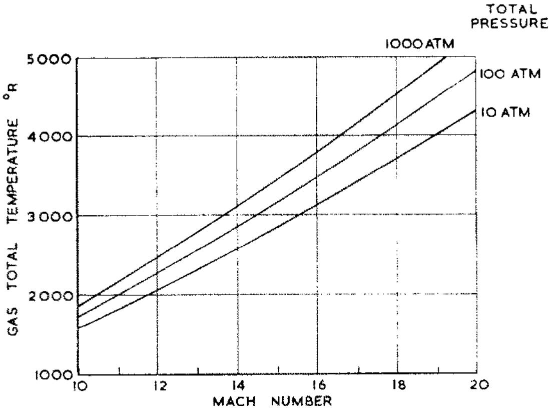

FIG. 1. Total temperatures for saturation of nitrogen in the test section at various Mach numbers and total pressures.

Molecular nitrogen should have no reactions with pure graphite until significant dissociation occurs (at about 8000°R at atmospheric pressure and at correspondingly higher temperatures at higher pressures [7]). Atomic nitrogen reacts with graphite to produce cyanogen, an extremely toxic gas. Since dissociation is to be avoided in the present work, the generation of cyanogen in the present heater system should not be expected. However, since there is always the possibility that unwanted impurities will get into the system or that local hot spots might occur, it is possible that the heated gas might contain harmful contaminants. During the early work, traces of cyanogen were found and since that time a hydrocyanic acid gas detector has been kept on hand to monitor the hot test gas [16]. Safety precautions for cyanogen are discussed in [17].

A general schematic diagram of the pilot hypersonic nitrogen tunnel is shown in Fig. 2.

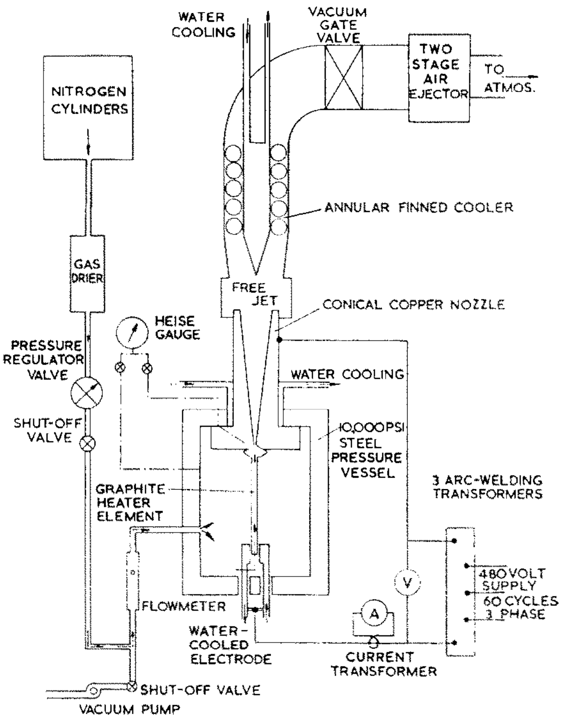

FIG. 2. Schematic diagram of the pilot hypersonic nitrogen tunnel.

Nitrogen gas from storage cylinders passes through a drier and a flowmeter into the high pressure stagnation chamber. The pressure in the chamber (and, therefore, the flow rate) is manually controlled by a pressure regulating valve. The gas in the chamber then passes through the graphite resistance element which is clamped between an electrical contact at one end and a heavy conical copper nozzle at the other. The hot gas from the graphite heater flows directly through the nozzle, then through a cooler, and finally through a two-stage air ejector at the downstream end of the system.

Details of the stagnation chamber and heater assembly are shown in Fig. 3. A solid copper "O" ring is used to provide a gas-tight seal

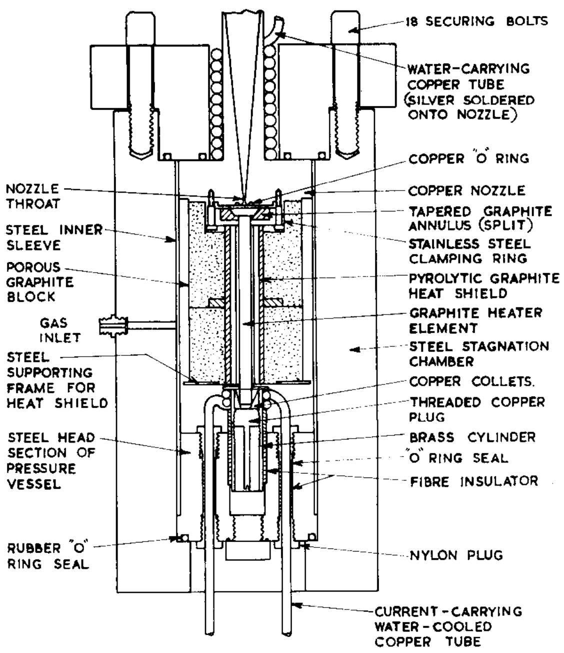

FIG. 3. Pressure vessel in section, showing heater element assembly.

between the graphite element and the copper nozzle to which it is clamped. The other end of the element is held by graphite collets in a water-cooled electrical contact. The electrical power leads are connected to the copper nozzle at one end and to the water-cooled brass tubes of the electrical contact at the other. A cylindrical radiation shield of graphite coated on the inside with 0·150 in of pyrolytic graphite is placed around the element.

The electrical power for the heater system is supplied by three standard arc welding auto transformers from a 480 V, 3 phase connection. The primaries are connected in delta and the secondaries suitably in parallel. This arrangement helps to balance the load on the primary, and hence reduce the peak primary line currents. Mechanically, the transformers are coupled by a chain drive to a small reversible a.c. motor and the setting of the current output (which is relatively independent of the secondary load resistance) is controlled by remotely activating the motor from the control console. A maximum output of 1200 A at 40 V is available.

A single precision Bourdon tube Heise gauge is used to read the pressure in the stagnation chamber and in the short chamber between the end of the heater and the nozzle throat. A Brooks high pressure flowmeter indicates the mass flow of gas through the system. A multi-range ammeter, in conjunction with current transformers, and a multi-range voltmeter are used to monitor the power supplied to the heater element. Tungsten–rhenium thermocouples have been used to measure the temperature of the outer wall of the graphite element, the outputs being recorded graphically on Speedomax pen recording machines.

Following the installation of a new heater element the complete system is first evacuated for several hours in order to eliminate the atmosphere which enters during assembly and to outgas the graphite element and other components of the system. The system is then filled with pure nitrogen. The vacuum gate valve is opened and the flow of cooling water started. The regulator is adjusted to give the required stagnation pressure downstream of the heater element, and the corresponding chamber pressure is also recorded. The cold mass flow is measured by the flowmeter. The current to the element is then switched on and set to the desired value, while the stagnation pressure is held constant at the original value. The particular test program is then carried through, the air ejectors being used when necessary to lower the gas densities in the nozzle and test section to reduce the heat transfer. (No attempt is made here to establish high Mach number flow in the nozzle.) At the completion of the test, the current is switched off and the system allowed to cool by continuing a small flow of cold nitrogen. Finally, the stagnation pressure is adjusted to its value during the test and the cold mass flow is measured as a check on the size of the nozzle throat.

The stagnation temperature of the nitrogen leaving the graphite heater is controlled by the current passing through the element. The stagnation temperature at a given current is estimated from the measurement of mass flow at that current in the following way. The mass flow, m, through the system can be expressed as $m = \Gamma A^* p_t/(RT_t)^{1/2}$, where A^* is the effective area of the tunnel throat, p_t is the gas total pressure, R is the gas constant for unit mass and T_t is the gas total temperature; Γ is a factor which, for a thermally perfect gas, depends on T_t only and is constant for a perfect gas with constant specific heats. It happens that for nitrogen in the range of temperatures and pressure under consideration, Γ is effectively constant. Consequently, the above equation gives T_t explicitly in terms of m. Using subscript $_0$ to denote values in the cold flow, we have $m_0 = \Gamma A_0^* p_{t_0}/(RT_0)^{1/2}$, where T_0 is room temperature. During normal operation, control is exercised so that $p_t = p_{t_0}$, and it is assumed that the effective throat area does not change during the test, that is $A^* = A_0^*$; it follows that the gas total temperature is given by $T_t = T_0(m_0/m)^2$. Clearly, this method of temperature estimation depends directly on the assumption that A^* is constant throughout the test, but the limitations of the method can be effectively condensed into this single assumption. The measurement of cold mass flow which is taken after a test shows whether A^* changed during the test as a result of deposition or erosion. The change in A^* due to thermal expansion is calculated to be very small, but so far no direct measurement of this effect has been obtained.

3. THE GRAPHITE RESISTANCE HEATER ELEMENT

Graphite is a material which is becoming of increasing importance in advanced projects because of its unique high temperature properties [18]. Several new types of graphite have recently been developed, such as pyrolytic graphite and impregnated graphites [19, 20, 21], and these are proving to be useful in the present investigations. Graphite sublimes directly from the solid to the vapor phase at 7200°R at atmospheric pressure. Although it has a high creep resistance, at high temperatures it does tend to creep under stress rather than to fracture, and it can withstand severe thermal shock. It is comparatively cheap and can be joined and fabricated fairly readily.

The present design of the heater system is only one of a number of forms which might have been developed to do the same job. Resistance heating was chosen on account of its basic simplicity and to enable the use of a cheap form of electrical power supply. With the method of heating and the heater material fixed, there still remains a wide range of possible element geometries; the overall size and shape of the element and the type of heat transfer passage must be selected. Several factors affect the choice of element geometry; firstly, the power generated within the element by the maximum available current must be sufficient to heat the required mass flow of gas; secondly, the structural properties of graphite influence the choice of wall thickness and overall configuration; thirdly, joints between graphite sections must either be made by threading or by using a graphite cement, and these joints are not impermeable to gases.

Exploratory tests to evaluate the usefulness of different types of element geometry and different grades of graphite [11] resulted in the adoption of a simple design consisting of a cylindrical rod of high density graphite containing a simple spiral gas passage. The single heat transfer passage eliminates many of the stability problems which are associated with multiple passage designs [11] and the spiral configuration offers several advantages: a long continuous passage is obtained in a small and rugged element; the gas flow, in circulating around the element, will reduce any tendency for the current to channel down one side [22] and there is an improvement in heat transfer in a spiral passage compared with that in a straight passage [23, 24]. Since the length of heat transfer passage required is much less for turbulent flow than for laminar flow, care in design has to be taken to select passage dimensions which ensure that the flow is turbulent [23].

A guide to the design of the element was found in an extension of heat transfer results in a straight-through constant-area passage [25] using an empirical correction to take account of the spiral [23]. Calculations were made for conditions of constant wall temperature and of constant heat flux to the gas. It is likely that the condition of heating existing in the element (away from the ends which have to be cooled) lies somewhere between these two. On the basis of the calculations a value of the ratio of passage length to equivalent diameter was chosen. Preliminary tests indicated a range of possible values of overall length and diameter of element which could be conveniently machined and which gave a suitable resistance for the available electrical power supply. A gas passage having a rectangular cross section was chosen because its equivalent diameter was smaller than for a square section with the same area. To avoid large pressure drops, the area of the gas passage must be such that the gas in the spiral has a low Mach number, and for the dimensions chosen the maximum Mach number in the passage was estimated to be about 0·04. From such considerations, the shallow spiral shown in Fig. 4 was selected. The passage length is approximately 27 in, with an equivalent diameter of 0·08 in. When operating at a stagnation pressure of 1000 lbf/in^2 the pipe Reynolds number based on the equivalent diameter of the passage is 76 500 when the gas is at room temperature and 11 800 at 5000°R. Since the transition pipe Reynolds number for this spiral is about 8500 it is believed that the flow through the heater element is turbulent [23].

The element is constructed in two parts which are machined from blocks of high density graphite. A spiral groove is machined in a cylindrical rod which is slipped into a cylindrical shell, and the two sections, fitted by hand to have good contact throughout their length, are held together by a small amount of graphite glue applied to the joint near the beginning of the spiral passage (Fig. 4). The ends of the element are designed specially to reduce conduction losses to the cooling systems while still maintaining good electrical contact. The heated gas leaves the spiral passage through a filter of twelve small holes to eliminate the swirl introduced by the spiral.

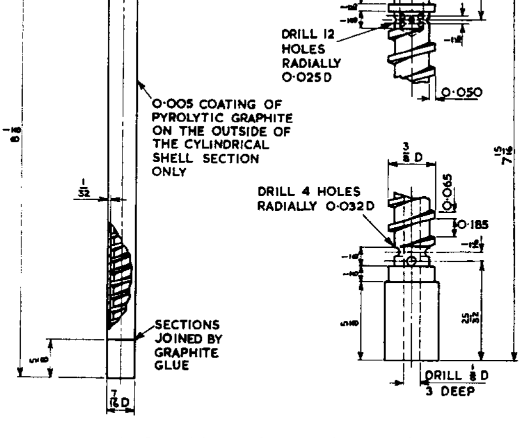

FIG. 4. Graphite resistance heater element.

Extensive tests using single spiral elements made from several different grades of graphite (National Carbon Company) revealed a key problem. Holes developed in the thin outer walls of the elements as a result of chemical reactions, involving impurities within the porous spaces of the graphite wall. (The graphites used in these tests were not completely impervious and some gas entered the spiral passage through the outer wall due to the pressure difference arising from the pressure loss in the passage.) Time histories of the element wall temperature distributions, obtained using tungsten–rhenium thermocouples recording on self-balancing potentiometers, showed that the appearance of a hole marked the end of the useful life of the element [11]. In an attempt to prevent this early failure from occurring, a series of elements, manufactured from one particular grade of graphite, were coated over the outside wall with an impermeable layer of pyrolytic graphite, nominally 0·005 inches in thickness. (The coating process was carried out by High Temperature Materials, Inc., of Boston.) Further, a supply of very high purity nitrogen, containing a total of six parts per million of oxygen and water vapor, was procured. During subsequent tests using coated elements, no holes appeared in the walls of any of these elements during repeated operation, under steady conditions, at gas temperatures up to 5000°R.

The first series of tests using coated elements was significant in that the heater system achieved its target performance for the first time, and the results were analysed in detail. A selection of results from this series of tests now follows.

4. SOME RESULTS FROM HEATER PERFORMANCE TESTS

Four coated elements, as described in Section 3, were tested in turn. During each test, readings were taken at several distinct current settings before operating continuously for 5 min at the highest current setting. Heater 2 was operated for a total of twenty-five tests (which implies a total running time at gas temperatures over 3000°R of over 2 h and at gas temperatures over 4000°R of over 1 h). For this heater the results from tests 1, 5, 10, 15 and 20 are presented. Heaters 1, 3, and 4, were each used several times but results are given only for one test of each. The elements were nominally identical and the stagnation pressure was always 1000 lbf/in^2. During the twenty-five tests using heater 2, the cold mass flow measurement taken between tests indicated some slight reduction in throat size resulting from the deposition of a film of solid material which appeared to contain graphite. A comparison of the measurements of cold mass flow taken before and after the series of tests indicated the film was less than 0·0005 in thick and was thought to arise as a result of the presence of impurities in the system. Supporting evidence of this was supplied by the way in which the deposits occurred. There was occasionally a definite reduction in mass flow after one test and not after the next, even though the latter test might have been a repetition of the former one, or a test carried out at increased values of current and consequently gas temperature. More significant deposits have been observed in the contraction ahead of the nozzle throat on previous occasions when appreciable quantities of impurity have been known to be present in the heater system [11]. Further, after a series of tests, a light film of graphite dust has generally been found in the corners of the spiral passage, which is likely to be the result of oxidation of the graphite by the small amounts of oxygen and water in the nitrogen supply. The amount and detailed appearance of the dust depend on the graphite which is used, and it is probable that the grain size and oxidation resistance of the material are major influences.

The performance of the heating system is expressed, for a given test of a given element, directly in the form of a graph of gas total temperature, T_t, against current, i, for a given total pressure. However, in order to express the performance of the system in a more general and significant fashion, it is desirable to use non-dimensional quantities instead of simply temperature and current (the experimental procedure must be planned so as to obtain sufficient information to present the results in non-dimensional form). The non-dimensional version of the independent variable i is taken to be σ defined by $\sigma = r_0 i^2/m_0 c_{p_0} T_0$, where r_0, m_0 and c_{p_0} are the values of the element resistance, the mass flow of gas and specific heat of the gas, all taken when no current is flowing, that is at room temperature T_0. The non-dimensional version of the dependent variable T_t is taken to be τ defined by $\tau = (T_t - T_0)/T_0$. To be able to obtain experimentally the plot of the total temperature parameter, τ, against the current parameter, σ, for a heater element it is necessary to determine the resistance when cold, r_0. It was found impossible to measure r_0 accurately because of the presence of contact resistances which, when the system is cold, are sometimes

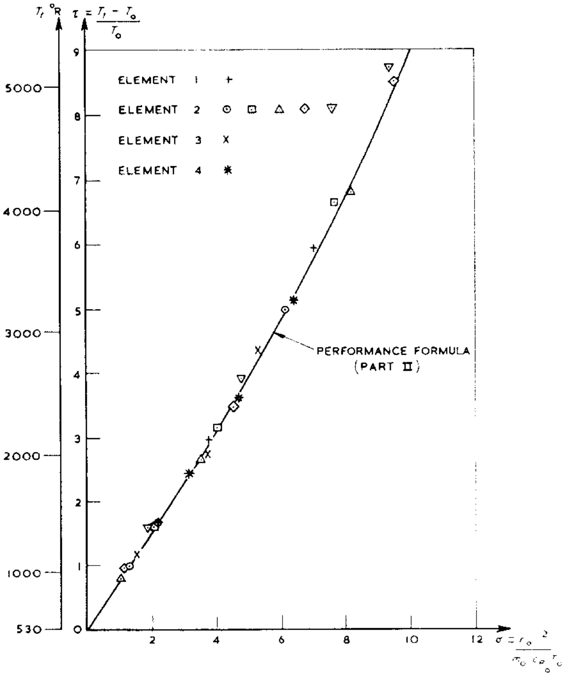

FIG. 5. Variation of total temperature variable τ with current variable σ, from test results.

of the same order as the element resistance. Consequently, an extrapolation procedure, based on the resistance measured at different values of current, was used [12].

Results for the four elements are shown in Fig. 5. It is seen that stagnation temperatures of 5000°R were achieved (in continuous tests of several minutes duration), and that there is consistency of results between different tests of the same element and between different (but nominally identical) elements. Also the experimental results are consistent with the theoretically derived performance formula (see Part II for details).

Table 1. Data for tested heater elements

	Test	Symbol	r_0 (Ω)	m_0 (lbs/s)	ω_0
Heater 1	1	+	0·053	0·0186	0·045
Heater 2	1	⊙	0·054	0·0186	0·040
	5	⊡	0·055	0·0181	0·035
	10	△	0·058	0·0178	0·031
	15	◇	0·060	0·0176	0·208
	20	▽	0·060	0·0176	0·026
Heater 3	1	×	0·049	0·0187	0·041
Heater 4	1	*	0·052	0·0184	0·045

The values of cold resistance, r_0, and the cold mass flow, m_0, for the tests considered are given in Table 1. It is seen from the values of r_0 that the elements did not initially have the same cold resistances; moreover, the cold resistance of heater 2 progressively increased with the number of times it was used. The effect of the film which formed in the orifice on the cold mass flow for heater 2 is seen in the given values of m_0. Also recorded in Table 1 is the pressure drop parameter, ω_0 defined as the ratio of the pressure drop down the element in the cold flow to the stagnation pressure (always 1000 lbf/in^2). The values of ω_0 in the first test of each heater were similar but for heater 2 decreased progressively with the number of tests performed. This effect has been observed with all coated elements which have been tested, but has not been found in the case of elements made completely from one type of graphite. The decrease in pressure drop resulted from a loosening of the spiral section within the outer shell of the heater element, which is probably an effect of creep. (Creep

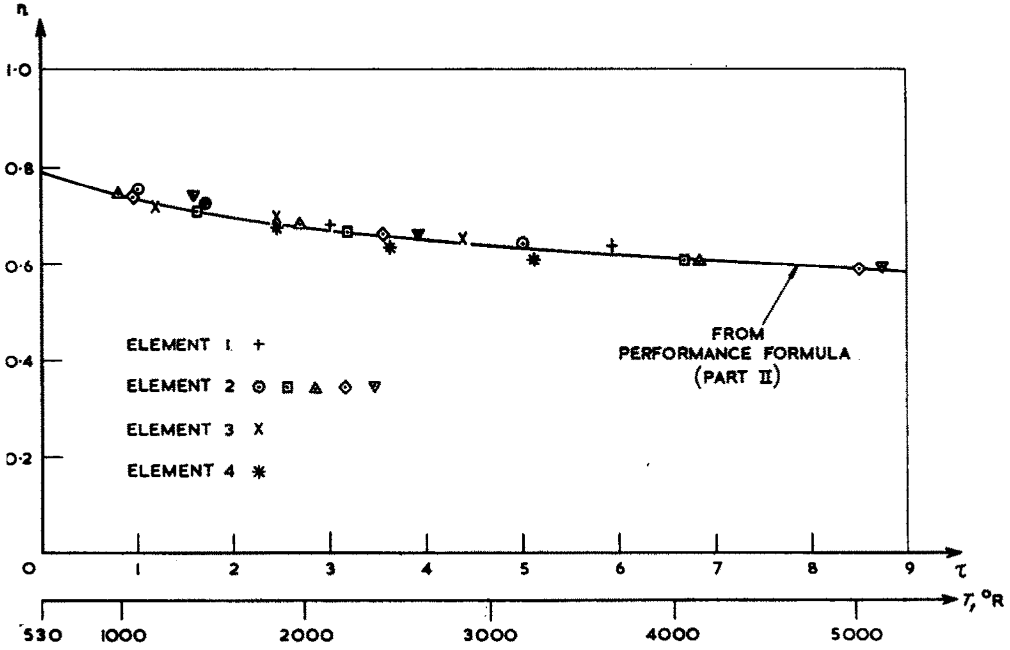

FIG. 6. Variation of efficiency η with total temperature variable τ, from test results.

would occur as a result of thermal stresses arising from the different coefficients of expansion of the pyrolytic graphite coating and of the base graphite.)

A plot of the overall efficiency of the heater system η, defined as the ratio of the heat received by the gas to the energy put into the system, against τ is shown in Fig. 6; η decreases from a cold value of 0·79 to about 0·59 at a gas temperature of 5000°R.

A more detailed analysis of the results shown in Figs. 5 and 6, based on some theoretical considerations of heater performance, is given in Part II of this paper [12].

5. CONCLUDING REMARKS

Using graphite resistance elements coated externally with pyrolytic graphite, steady operation of the heating system of the pilot hypersonic nitrogen tunnel has been achieved for periods of over 5 min at gas temperatures up to 5000°R. (The operating times were limited by the amount of compressed air available for the ejector system.)

Many difficulties which were encountered in the development of the system are thought to have been caused by chemical reactions in the heater involving substances other than pure nitrogen and pure graphite. The formation of holes in the outer walls of elements used in earlier tests was probably a result of chemical reactions taking place during the passage of impurities through a permeable graphite wall. An impermeable coating of pyrolytic graphite over the outer wall of the element has been entirely successful in preventing the occurrence of these holes, and further significant improvements in heater performance have been obtained as a result of attention being concentrated on methods of eliminating all contamination from the system. The use of very high purity nitrogen, careful procedures for cleaning and handling components, and outgassing of the system before use, are considered necessary to obtain optimum performance. Since there will inevitably be traces of impurities which cannot be entirely eliminated, a dense graphite with high resistance to oxidation should be used so that the effects of any impurities will be minimized. (Oxidation within the element can result in the contamination of the nitrogen stream by solid graphite particles, and in the reduction of the size of the nozzle throat by the deposition of products of chemical reaction; both these effects are highly undesirable from the point of view of conducting aerodynamic tests.)

A coating of pyrolytic graphite over all surfaces of the element would provide excellent resistance to oxidation, but the technical problems of such a solution have not yet been fully explored. Another promising possibility is offered in the use of a relatively new material, recrystallized graphite (National Carbon Company), which has a very high resistance to oxidation, high density and very low permeability (compared with ordinary grades). Since the permeability of recrystallized graphite is low, and moreover since it can be reduced to near that of pyrolytic graphite by a process of impregnation, it may be possible to use uncoated elements made from this material.

More development work is required to extend the operation of the heater system to higher stagnation pressures (around 10 000 lb/in^2) so that the densities and Reynolds numbers in the tunnel test section can be varied over a wide range. Problems concerned with the structural soundness of the element and the current-carrying capacity of the electrical contacts might occur, but these are not likely to be severe. The copper throat of the nozzle will probably melt when the flow there ceases to be laminar, but the ultimate solution to this problem is available in the use of the same material for the throat as for the heater element itself. An attractive possibility is offered in the use of a pyrolytic graphite throat which can be manufactured using a plating process. The present method of estimating gas total temperature, involving the metering of mass flow, might present experimental difficulties at higher pressures. Also, some of the simplifying assumptions and approximations used in the analysis of the present heater performance (Part II) may have to be modified, but the theoretical basis should still be applicable in an extension to higher pressures.

The present heater can be used to heat a stream of any inert gas. For example, a similar unit has been used with Freon, in experiments concerned with temperatures of dissociation [26], and with helium. If helium is used, the heater can supply gas temperatures (3000°R) which are sufficient to avoid condensation in an expansion to Mach numbers greater than 60, and can also supply gas conditions simulating stagnation point heat flux as for re-entry.

With the development of a successful heater system for use with nitrogen, a major problem in the design of a truly continuous wind tunnel to operate with a diatomic gas at Mach numbers up to 20 has been essentially solved. The graphite heater is now near to satisfying the full heating requirements for hypersonic nitrogen tunnels. The gap between the actual and required performances should be reduced by the continued use of the pilot nitrogen tunnel to extend the development to higher pressures and the use of a second nitrogen tunnel to investigate flow conditions [27]. Also the heating system will have application in the design of a similar system for heating air as new non-oxidizing materials become available.

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Résumé—Un système de chauffage a été étudié pour une soufflerie hypersonique continue à azote, fonctionnant à des nombres de Mach allant jusqu'à 20. Ce dispositif utilise un élément de graphite chauffé électriquement et percé d'un trou en spirale pour le passage du gaz.

On a utilisé une petite soufflerie pilote à azote pour étudier ce réchauffeur. La soufflerie est prévue pour fonctionner à une pression d'arrêt maximum de 700 kg/cm^2, mais le travail ci-dessous se rapporte à un fonctionnement avec pression d'arrêt ne dépassant pas 70 kg/cm^2. Cet article concerne surtout la mise au point du système de chauffage et non l'établissement d'un écoulement à nombre de Mach élevé dans la section d'essais (pour ceci on utilise actuellement une seconde soufflerie hypersonique).

La température d'arrêt nécessaire pour éviter la condensation de l'azote dans la veine d'essais à $M = 20$ est environ 2200°K. Les principales difficultés que l'on rencontre pour atteindre une telle température, inférieure à celle pour laquelle l'azote commence à se dissocier et à réagir avec le graphite, sont causées par les réactions chimiques qui se produisent entre les substances autre que l'azote pur et le graphite pur. La pureté du gaz d'alimentation, la propreté des équipements et la qualité du graphite sont de la plus haute importance. On a trouvé qu'une fine couche imperméable de graphite pyrolytique à l'extérieur de l'élément chauffant évitait la formation de trous dans la paroi extérieure, ce qui se produit avec des éléments non enrobés. De tels éléments protégés ont été régulièrement utilisés pour obtenir des température d'arrêt du gaz allant jusqu'à 2200°K à des pressions d'arrêt de 70 kg/cm^2 (Les résultats détaillés sont présentés dans la deuxième partie). L'adaptation du système de chauffage à des pressions plus élevées ne devrait susciter que des difficultés mineures. Des gaz autres que l'azote ont été utilisés avec succès pour l'appareil actuellement en usage, et l'on escompte outre que l'expérience acquise avec le système actuel pourra être utilisée pour un appareil de chauffage à air d'une conception analogue dès qu'on disposera de matériaux inoxydables appropriés.

Zusammenfassung—Für einen mit Stickstoff betriebenen und in kontinuierlichem Betrieb $Ma = 20$ erreichenden Hyperschall-Windkanal wurde ein Erhitzer entwickelt in Form eines elektrisch direkt beheizten Graphitstabes mit einer spiralförmigen Nut für den Gasdurchfluss.

Für die Entwicklung des Erhitzers wurde ein kleiner stickstoffbetriebener Hyperschall Modellkanal benutzt. Der Kanal war für einen höchsten Ruhedruck von 700 at ausgelegt, berichtet wird aber nur über Versuche mit Höchstdrucken von 70 at. Hier wird nur die Entwicklung des Erhitzers, nicht die Erzeugung der Hyperschallströmung in der Messstrecke beschrieben. (Für letztere diente ein zweiter Hyperschall-Kanal.)

Eine Ruhetemperatur von 2780°K ist erforderlich, wenn bei $Ma = 20$ Stickstoffkondensation in der Messstrecke vermieden werden soll. Bei dieser Temperatur tritt noch keine Dissoziation des Stickstoffs oder Reaktion mit dem Graphit auf. Hauptschwierigkeit ist jedoch, die von Verunreinigungen des Stickstoffs oder des Graphits herrührenden Nebenreaktionen zu verhindern. Höchste Reinheit sowohl des Gases wie des Graphits und allgemeine Sauberkeit der Versuchseinrichtung erwiesen sich daher als sehr wichtig. Mit einem dünnen, auf die Aussenseite des Heizelements aufgebrachten, undurchlässigen Überzug aus pyrolytischem Graphit konnten Ausfressung ender Heizfläche verhindert werden, die andernfalls zu beobachten waren. Solche Heizelemente mit Schutzschicht wurden zur Erzeugung von 2780°K bei Drücken bis zu 70 at regelmässig benutzt. Die einzelnen Versuchsergebnisse werden in Teil II mitgeteilt. Beim Ausbau des Heizsystembetriebes auf höheren Druck sind nur geringfügige Probleme zu erwarten. Ausser Stickstoffgas haben sich schon andere Gase für den gegenwärtigen Heizapparat bewährt. Es liegt auch auf der Hand, dass die Erfahrungen, die mit dem hier beschriebenen System gemacht wurden, in der Konstruktion eines ähnlichen Heizgerätes für Luftverwertet werden können, sowie nichtoydierende Werkstoffe verfügbar werden.

Аннотация—Разработана система нагревателя для гиперзвуковой аэродинамической трубы с потоком азота при числах Маха до 20. В системе используется электрический нагреватель из графита со спиральным проходом для газа.

Установка представляет собой небольшую гиперзвуковую аэродинамическую трубу с потоком азота. Труба рассчитана на максимальное давление заторможенного потока газа до 10 000 фунтов/кв.дюйм, но исследование, описанное в статье, проводилось при давлении 1000 фунтов/кв.дюйм. здесь рассматривается система нагревателя для аэродинамической трубы, а не способы достижения больших чисел Маха в рабочем участке (для этого используется другая гиперзвуковая аэродинамическая труба с потоком азота).

Температура заторможенного потока, при которой отсутствует конденсация азота в рабочем участке при числах Маха около 20, приблизительно равна 5000°R. Основные трудности получения температуры ниже той, при которой азот начинает диссоциировать и, таким образом, вступает в реакцию с графитом, связаны с химическими

реакциями между примесями в газе и графите. Поэтому чистота газа и оборудования, а также сорт графита имеют первостепенное значение. Для предотвращения образования отверстий в наружной стенке нагреватель покрывается сверху тонким непроницаемым слоем пиролитического графита. Такие элементы используются для получения постоянной температуры газа до 5000°R при давлении 1000 фунтов/кв.дюйм.

Расширение применения обогревателя для работы при повышенном давлении не представит больших турдностей.

Другие газы, кроме азота, могут применя ться успешно с настоящей системой обогревателя и предполагается что дальнейший опыт с описанной системой поможет спроэктировать подобный обогреватель для воздуха при условии что будут найдены подходящие, неокисляющиеся матерьялы.