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The coaxial and triaxial fast response surface thermocouples, developed at the Midwest Research Institute and originally manufactured by C.E. Moeller at Motech Company, have been manufactured by MEDTHERM Corporation, Huntsville, Alabama since 1970.

58. Thermocouples for the Measurement of Transient Surface Temperatures

C. E. Moeller

Midwest Research Institute, Kansas City, Mo.

The measurement of rapidly changing surface temperatures of metal walls has been of prime interest to investigators who are studying the internal ballistics and barrel life of ordnance pieces, the design and operation of rocket nozzles, and heat-transfer operations in various laboratory equipment. Surface temperature can be measured by a thermocouple, but for accurate measurement the configuration of the thermocouple must not interfere with the transfer of heat to or from the metal surface. The thermal junction must be in a plane parallel, and as close as possible, to the exposed surface. Moreover, the heat flow through the thermocouple body must be nearly identical to that of the undisturbed metal wall. Hence, the body and probe of the thermocouple should be machined from materials that have the same thermal properties as the wall in which the thermocouple is mounted.

The first thermocouple capable of measuring transient temperatures at the internal surface of a gun barrel was developed in Germany during World War II and described in a paper by Hackemann.[1] The thermocouple had a thermal junction in the form af a plane parallel to and approximately 2 microns (80 microinches) beneath the surface of the sensing probe. Soon after the design of the Hackemann thermocouple was made available, various organizations in the United States initiated programs under government sponsorship to develop and use this type of surface thermocouple. Purdue University used thermocouples of this general configuration for measuring bore temperatures of machine guns (reported by St. Clair in 1949[2]). An improved design of this thermocouple was described in a later paper (1953) by Chenoweth at Purdue.[3] During this same period of time, Midwest Research Institute developed a thermocouple somewhat similar to the original Hackemann design, and its development and application were described by Bendersky in 1953.[4] Other investigators working on the same general problem were Armour Research Foundation,[5] Geidt of Detroit Controls Corporation,[6] and the U. S. Naval Proving Ground.[7]

DESIGN

The three designs which are now commercially available were developed by Detroit Controls Corporation, Midwest Research Institute, and the U. S. Naval Proving Ground. Figure 1 indicates these desgins and the differences among the designs. The thermocouple developed by Detroit Controls Corporation [Fig. 1(a)] is fabricated in a manner very similar to the original Hackemann design. A steel body is prepared with a small hole in one end. A nickel wire is oxidized in a gas flame so that the surface of the wire is coated by nickel oxide, which is an effective electrical insulation to approximately 800°F for sustained temperatures, and to 2000°F for transient temperatures. The coated nickel wire is then inserted in the small hole in the iron body, and the iron is swaged firmly around the insulated nickel wire to hold the wire rigidly and prevent its movement. After the end of the assembly has been polished, it is electrically nickel-plated and then polished to the desired thickness. The thermal junction is formed at the inner face of the nickel plating and the end of the iron body. The plating can be of any desired thickness between 0.0002 and

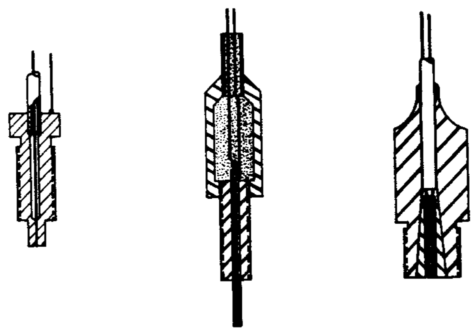

FIG. 1. Thermocouples developed by (a) Detroit Controls Corp., (b) Midwest Research Institute, and (c) U.S. Naval Proving Ground.

0.002 inch. For a particular application, the body can be threaded, or it can be held in place in a metal wall by the use of an adapter. The nickel wire serves as the negative metal of the thermocouple, and the iron body serves as the positive metal.[8]

The thermocouple design in Fig. 1(b), which was developed at Midwest Research Institute[4] (MRI), varies from the original design in three ways. First, the center wire is not insulated by nickel oxide; instead, it is coated with an aluminum oxide insulation and can be used at elevated temperatures to and above 2000°F for extended periods of time. Also, the center wire can be of any material desired, such as Alumel, constantan, platinum alloys, etc.

Second, tubing is used instead of a machined body. The coated wire is placed in the tubing, and the assembly is pulled through a wire-drawing die; the diameter of the tubing is thereby reduced. Thus, the tubing rigidly holds the insulated center wire. This technique permits the making of thermocouple probes which can have diameters down to or even less than 0.015 inch, and of any desired length up to 10 or 15 inches.

A third variation from the original design has to do with the method by which the thermal junction is formed at the end of the assembly. After the end has been cut and polished, it is vacuum-coated with a thin layer of either nickel or rhodium. (Rhodium has greater resistance to high temperature oxidation than nickel.) Vacuum-coating permits the depositing of an extremely thin layer of metal on the end of the assembly, thereby producing a controlled and uniform thickness. The plating thickness generally used is about 0.00004 inch or 1 micron; however, greater thicknesses can be deposited. The tubing assembly can be held in any type of threaded mounting body; hence, it can be used in widely varying types of applications.

The third design of the original thermocouple, developed by the U. S. Naval Proving Ground [Fig. 1(c)], varies even more from the original design than the MRI version. Initially, the two thermocouple wires are flattened into ribbons and then sandwiched between thin sheets of mica and the split sides of a tapered pin. The assembly is then pressed into a matched tapered hole in the mounting body; hence, the ribbons of thermocouple metals are rigidly held in place and insulated from each other as well as from the mounting body. The end of the assembly is abraded with No. 80 grit abrasive paper, and the thermal junction is thus formed by small slivers of metal which are carried over from one thermocouple metal to the other. The thermocouple can be made of any desired metal combination and used in any type of mounting body that is large enough to hold the tapered pin assembly.[7]

Generally, the thermal junctions of all three of these designs can be formed by abrading the end of the thermocouple with coarse abrasive paper. However, the distance between the junction and the exposed surface may vary, and is unpredictable. In most applications, this distance may not be important.

The theoretical time constant of the surface thermocouple can be computed; it is assumed that the sensing surface is exposed to a theoretical step change. Through the use of the Gurney-Lourie charts,[8] a time constant of less than 1 microsecond is computed for the thermocouple having a 1 micron plating thickness, that is, the thermal junction is 1 micron or 40 microinches from the exposed surface. As the plating thickness increases, the time constant rapidly increases.

The experimental time response of the surface thermocouple probe of Fig. 1(c) was determined by the Nanmac Corporation. The surface thermocouple was mounted in the wall of a 4-inch diameter shock tube. A temperature change was recorded in less than 10 microseconds during a hydrogen-oxygen detonation.[9]

APPLICATIONS IN ORDNANCE SYSTEMS

The surface thermocouple has been used in a wide variety of applications, both by government agencies and in industrial research laboratories. A few of the typical applications and some of their results are described in the subsequent sections. Figure 2 is a record of the bore temperature of a 60-caliber machine gun barrel.[10] This record is typical of the response of which the thermocouple is capable. The maximum temperature is reached in approximately half a millisecond; however, the most rapid temperature change occurs during the initial time when the sensing surface of the thermocouple is abruptly exposed to the hot gases as the projectile travels past it. This time interval is probably in the order of 50 microseconds.

The importance of having the thermal junction as close to the surface as possible is shown in Fig. 3. The transient temperature curves have been calculated at various depths in the nozzle of a 57-millimeter recoilless rifle, based on surface temperature measurements with the MRI thermocouple.[11] The maximum surface temperature rise, approximately 900°F, occurs in about 4 milliseconds. However, at a plane only 0.002 inch from the exposed surface, the maximum rise has dropped to slightly above 700°F. Similarly, at a plane of 0.005 inch from the exposed surface, the maximum change has been reduced to less than 600°F. At 0.010, the maximum has been reduced to less than 400°F, and the very rapid surface temperature change and the extreme temperature peak are no longer indicated. However, these temperatures are based on extremely rapid temperature changes at the surface created by very high heat-transfer rates. In applications with lower heat-transfer rates, the importance of having the thermal junction very close to the surface is not so critical.

Determination of the temperature gradients which occur at various times within a particular metal wall is an important result of analysis of the surface temperature measurements. These gradients in the metal wall are created by extremely high heat-transfer rates created by the high velocity and high temperature gases from the burning propellant, 72 Btu per second square inch maximum. This rate is equivalent to 37,300,000 Btu per hour square foot. Figure 4 records the temperature gradients in the metal wall of the nozzle of the 57-millimeter recoilless rifle at various times during the ballistic cycle, as calculated from the surface temperature shown in Fig. 3. The maximum thermal gradient represented by these data is approximately 100°F per 0.001 inch. Calculations of the thermal gradients are essential for determining transient thermal stresses which exist at the inner surfaces of gun barrels during the firing of

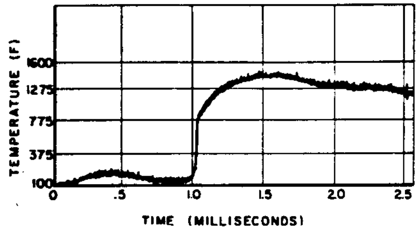

FIG. 2. Typical record of the bore temperatures of a 60-calibre machine gun barrel, indicating thermocouple response to rapidly changing temperatures.[10]

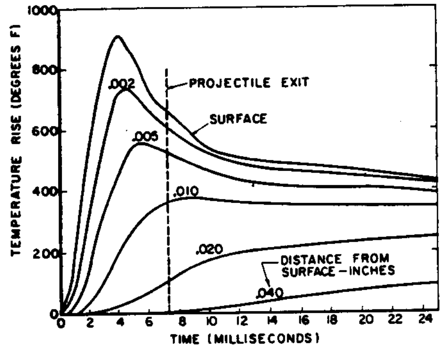

FIG. 3. Transient temperature curves calculated at various depths in the nozzle of a 57-millimeter recoilless rifle.[11]

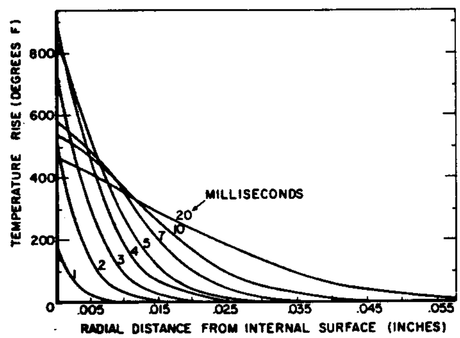

FIG. 4. Temperature gradients in the wall of the nozzle of a 57-millimeter recoilless rifle at various times during ballistic cycle. Maximum heat transfer rate is 72 Btu per second square inch.[11]

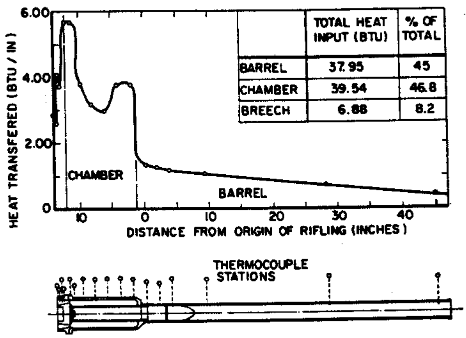

FIG. 5. Total heat input to a 57-millimeter recoilless rifle from surface temperature measurements.[11]

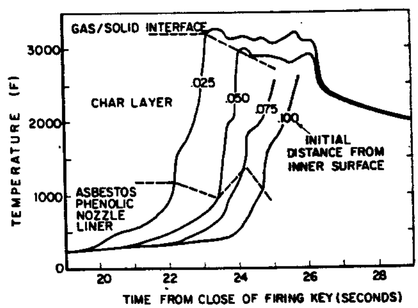

FIG. 6. Temperatures at various depths in nozzle insulation of a research rocket motor.[13]

a projectile. Thermal stresses are created because of temperature differences of adjacent points in the metal wall. Thermal expansion would cause the hotter metal to expand, but the metal is restrained by the cooler adjacent metal. Hence, a complicated stress pattern is formed because of the temperature gradients.

The total heat transferred to the various portions of the recoilless rifle from the propellant gases can be determined as part of the calculations of the heat-transfer studies. Figure 5 indicates the total heat input distribution to the rifle during the firing of a projectile, based on calculations using surface-temperature measurements at 17 different locations along the nozzle of the breech, the walls of the combustion chamber, and the barrel of the rifle. The effects of various parameters in any type of rifle, gun, or rocket motor can be determined by this technique. An example of the technique applied to rocket ignitors is described by Nanigian and others at the U. S. Naval Propellant Plant.[12]

An important feature of the surface thermocouple, which was used to advantage at the U. S. Naval Propellant Plant, is the capability of the thermocouple to maintain its thermal junction by abrasion. Figure 6 indicates the temperatures of four different thermocouples which were located at various depths in nozzle insulation of a research rocket motor.[13] During the firing of the rocket nozzle, the liner gradually charred and eroded away, exposing to the hot gases first one thermocouple, and then the next, and then subsequent ones. All four thermal junctions were eroded flush with the inner surface of the nozzle, but still the thermal junctions on the first two thermocouples (platinum-platinum 10% rhodium) remained intact. The third and fourth thermocouples were Chromel-Alumel. Analysis of these temperature records provided valuable information as to the behavior of the asbestos phenolic nozzle liner and the manner in which the charred layer progressed as the liner eroded away.

INDUSTRIAL APPLICATIONS

Investigators at the University of Wisconsin have studied heat transfer in engines under a wide variety of conditions.[14] A simplified version of the Midwest Research Institute thermocouple was used as a basis of the experimental work. Figure 7 shows the installation of the thermocouple in a Lauson L-Head engine and its response at an engine speed of 2400 revolutions per minute. The record indicates an approximate 15°F temperature change during 3½ milliseconds. The lower nickel wire of the thermocouple arrangement and the iron wire were used to determine the temperature of the cylinder head on its water-side. Heat-transfer rates and coefficients were determined under a wide

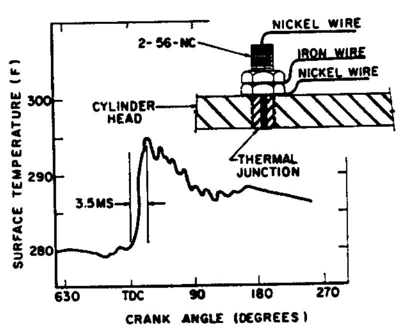

FIG. 7. Response and typical installation of MRI surface thermocouple in a Lauson L-head gasoline engine, 2400 revolutions per minute.[14]

variation of operating conditions for various types of fuel additives.

The thermocouple was also used to determine the effects of deposits on the cylinder head surfaces of a CFR engine. The engine was started with a clean thermal junction and then allowed to operate continuously to obtain various thicknesses of deposits. Figure 8 is typical of the surface temperatures in the CFR engine at 1000 revolutions per minute, both at the beginning of a test with a clean sensing surface of the thermocouple, and at the end of a test with a deposit covering the sensitive surface. The result is a lowering of the average surface temperature of the cylinder wall by 12 to 15°F. The rapid fluctuations of the surface temperature are dampened, a fact which indicates that the deposit reduces the heat-transfer rate from the gases to the surface. By the use of records such as these, and the measurement of the deposit thickness after a run has been completed, the thermal conductivity of the deposit can be calculated, as well as a time average temperature of the deposit-gas interface. These results are significant since they are obtained without disturbing the deposits or imposing any unrealistic requirements on the over-all heat-transfer phenomena.

The surface thermocouple enables other types of basic research to be conducted on phenomena that were not formerly considered possible, such as the experimental measurements of the surface temperatures of a metal wall in contact with boiling water. At the University of Kansas, other investigators are conducting a basic research program on nucleate boiling, and using a miniature version of the MRI thermocouple.[15] The probe has a 0.015 inch outside diameter and a 0.003 inch diameter insulated center wire. The miniature assembly is interference-fitted into a

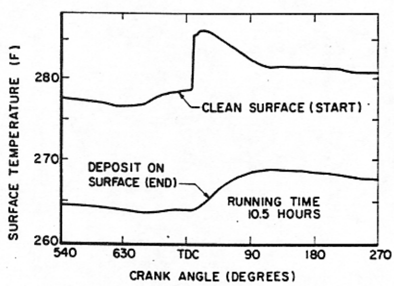

Fig. 8. Internal surface temperatures of CFR gasoline engine, 1000 revolutions per minute, for carbon deposit studies.[14]

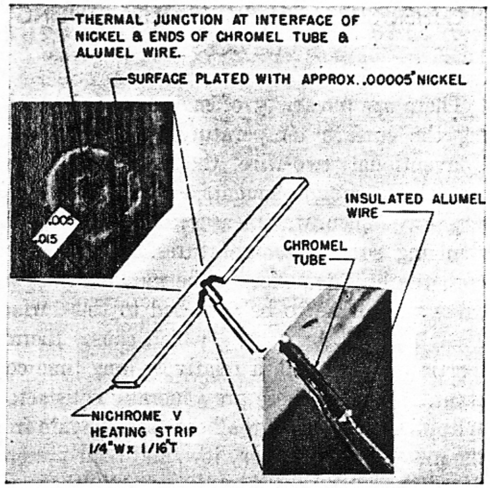

Fig. 9. Miniature surface thermocouple mounted in a heating strip for nucleate boiling studies.[15]

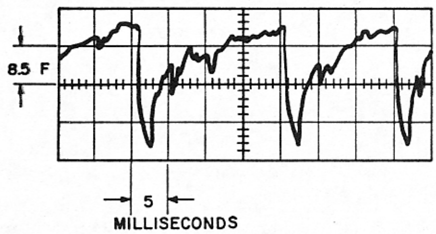

Fig. 10. Surface temperature variation at interface of metal surface and water during nucleate boiling at 135,000 Btu per hour square foot.[15]

nichrome heating strip and the surface of the probe polished flush with the surface of the heater strip. In initial tests, the thermal junction was created by a layer of nickel, Fig. 9, but in subsequent tests the surface of the thermocouple probe and the heater was abraded with No. 160 abrasive paper to carry slivers of the tubing (Chromel) over to the center wire (Alumel).

During the boiling studies, heat is generated with dc voltage across the heater at heat rates up to 200,000 Btu per hour square foot. The heater assembly is submerged in water in an open vessel, and the surface temperatures measured while nucleate boiling occurs. A typical record of the surface temperature variation is shown in Fig. 10. A significant feature of this record is that the temperature of the metal surface drops 25 to 30°F in 2 milliseconds. The character of this temperature change has led the investigators to propose a new hypothesis about nucleate boiling, which they call "microlayer vaporization."

OTHER SURFACE TEMPERATURE-SENSING DEVICES

There are a variety of methods of determining the surface temperature of a metal wall. Conventional two-wire thermocouples, resistance thermometer elements, and thermistors will not give accurate measurements of rapidly changing surface temperatures. They interfere with the heat transfer to the metal surface because they have to be attached to this surface. Their mass absorbs heat, which causes thermal inertia and, in turn, a relatively long time constant. However, these are generally satisfactory in applications where the heat-transfer rate from the metal surface is very low, and their presence does not mechanically interfere with other components of the system.

Other elements used for measuring transient surface temperatures include radiation-sensing devices and thin film elements, either resistance or overlapping thermocouple metallic films deposited on an insulating film. The time constants of some of the elements in this group are in the micro-second range, and so they have the same type of response as the surface thermocouples described in this paper.

A comprehensive review of the use of metal films in transient surface temperature thermometry is given by Hall and Hertzberg.[16] The principal application of the thin-film resistance device is the measurement of the heat ransfer in shock tubes and shock tunnels. The local heat-transfer rates can be calculated by the conventional heat conduction procedures. The thin-film devices are limited to applications with a relatively small surface-temperature rise.

Measurement of the surface temperatures by radiation pyrometry techniques requires that the surface being measured can be viewed by the detector. In many cases, such viewing is impossible or highly impractical. Where the surface is clearly visible, however, radiation detection systems are highly successful. They are particularly suitable for applications involving surface temperatures above the melting points of thermocouple metals.

COMMERCIAL SOURCES OF THE SURFACE THERMOCOUPLE

Three thermocouple designs are now commercially available (see Fig. 1). Thermocouples of the design developed by the Detroit Controls Corporation can be procured from Advanced Technology Laboratories at 369 Whisman Road, Mountainview, California. Those of the design developed by Midwest Research Institute are now currently available from the Motech Company, Box 6009, Kansas City 10, Missouri, and those developed by U. S. Naval Proving Ground from the Nanmac Corporation, P. O. Box 8, Indian Head, Maryland. Although only three designs are shown in Fig. 1, a wide variety of models is available from each company.

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