Gas Cooled Probe Protectors

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ABSTRACT

The design and testing of a gas cooled probe protector shell is described. Standard optical probes are limited to relatively low temperature and mild environmental conditions. By enclosing such probes in concentric air-cooled stainless steel tubes with a brazed sapphire window at the end, their operating limits can be greatly extended. Gas cooling eliminates the facility requirements and leak hazards of water-cooled probes. Low gas flow rates have been demonstrated to maintain a probe at less than 100°C in a 600°C quiescent environment.

Keywords: endoscope, high, temperature, gas, cooled, probe, protectors, optical

1. INTRODUCTION

Probes used to control and inspect industrial processes must often function in very demanding environments. Common process temperatures range from a low of the boiling point of liquid nitrogen to a high of metals melting, ceramics sintering, or combustion. Pressures range from high vacuum to thousands of atmospheres. Extremes of reactivity include pure fluorine, both ends of the acid/base scale, and oxygen rich combustion. Corrosion is common, temperature cycling induces metal fatigue, and solids in the fluid may cause impact damage or probe tip fouling.

Standard probes require relatively clean and mild environments that greatly limit their usefulness in industry. Usually measurements are taken through viewports or specially adapted windows. If a probe must be inserted, a massively and inefficiently water-cooled probe protector is developed for each user, designed to survive their specific conditions.

A set of standard gas sheathed protective probe shells can enable common probes to be used in severe environments with minimal disturbance of the sensed environment. Internal gas flows are used to cool and insulate, while external flows provide heat shielding and surface cleaning. The hot outer shell of these probes also leaves the environment almost unperturbed. Gas shielding/cooling uses minimal facilities and is not susceptible to the catastrophic failure that is characteristic of water cooled probes and can jeopardize the entire facility. Temperatures from -200°C to 700°C, and pressures up to 5,000 psi can be tolerated, while chemically inert housing materials allow operation in highly caustic and acidic environments. Fluid jets at the probe tip can be used to prevent the process fluid from fouling the probe inputs. Optical shells using sapphire windows can tolerate almost any harsh environment.

2. CURRENT TECHNOLOGY

Optical diagnostics are widely used in industry to control and inspect a variety of processes. Endoscopes are used for inspection, pyrometers measure temperature, spectrometers measure chemical composition, and fiber optics are increasingly used to diagnose many system chemical and physical properties. The endoscopes that are currently available are severely limited, tolerating temperatures only from -50 to 150°C, pressures less than 100 psi, and no abrasive or chemically corrosive environments**.** Processes that allow sediment buildup make endoscope use awkward when the viewing window becomes obstructed and must be cleaned. These characteristics greatly limit the usefulness of endoscopes in industrial processes, which often occur in chemically or physically harsh environments.

The standard industrial approach to protecting endoscopes, or probes in general, from a high temperature environment is to add a high flow rate water jacket. Water cooled probes are primarily simple designs where the volume of water flow circulated through the probe is determined by the maximum possible heat flux that must be carried away by the water, together with a large safety factor. Rarely are the subtleties of the internal fluid flow considered. The large safety factor is required to avoid without question the problem of boiling thermal runaway. The probe diameter must also be increased dramatically to provide adequate water flow. Furthermore, the probe tip cannot sense through water, so awkward tip designs must be used, often adding air cooling.

The thermal runaway problem (Fig. 1) of water begins when there is inadequate local heat transfer and a local hot spot develops. Usually there is either a higher heat flux from the environment or insufficient local water flow. If the heat flux generated at the spot is greater that the cooling rate of the liquid, the extra heat will vaporize some of the liquid and create a water vapor bubble at the hot spot. The creation of this bubble immediately lowers the heat transfer to the fluid at the hot spot, causing an unstable feedback where the temperature of the hot spot to increase even more rapidly. For enclosed flows the situation is even worse, because the vapor bubble creates a high local pressure that blocks the flow, stopping all of the cooling, and can lead to a catastrophic failure of the entire system. This problem is avoided by using gas cooling, where the heat transfer increases near a local hot spot, as shown in Fig 1.

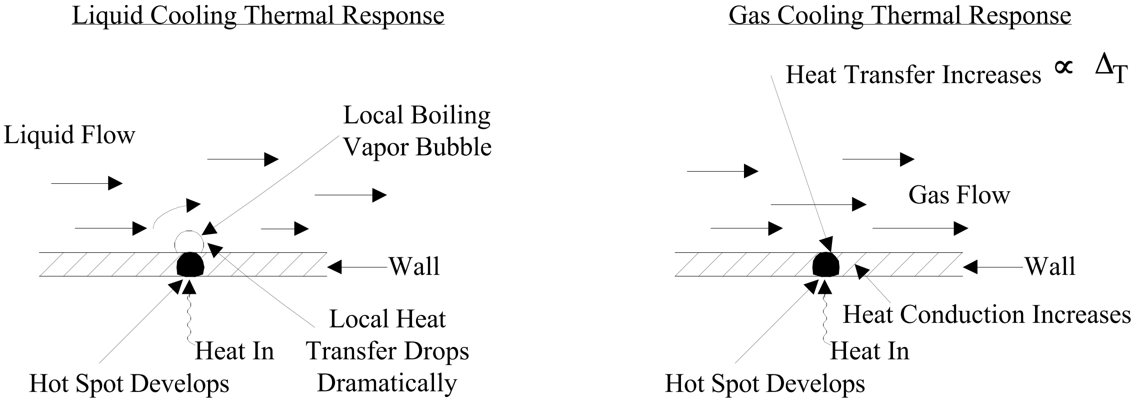


Figure 1. Schematic of thermal runaway process for liquid and gas cooling.

3. THE ENVIRONMENT

The characteristics of process environments must be discussed to define both the physical constraints and the economics of the applications. Certain types of processes under extreme conditions are widespread, including cryogenic processing, combustion, and many types of materials processing. These processes can take place at pressures that require essentially zero leak rate to maintain a vacuum, or many atmospheres of pressure. Temperatures can vary from - 200^{o}C to above 3000^{o}C. These are the extremes of the environmental demands on a probe shell, excluding plasma processing where temperatures can be much higher. The extreme temperatures are put in perspective by the fact that standard probes have a specified use temperature of 100-200^{o}C and in extreme cases 400^{o}C. The reason for these temperature limits is usually the inclusion of sealants, glues, or primary materials made of some type of plastic.

Other factors are also very important to probe shell design. Thermal shock, thermal cycling, thermal stress, thermal fatigue, and high heat fluxes are all relevant considerations in high temperature design. Chemically reactive environments include pure fluorine, strong acids and bases, and excess oxygen in a flame; reactivity is greatly enhanced at elevated temperatures. Solids in the fluid may cause impact damage or fouling of the probe tip. The extremity of the conditions almost always translates into a lack of diagnostics for monitoring the process. The process cost and the benefits from diagnosis determine how expensive a probe can be. To further add to the environmental limitations of available probes, seals are required to both seal the probe in the process stream and the joints between the sensor and the probe body.

Temperature monitoring is the most common industrial diagnostic requirement, usually fulfilled by thermocouples or by optical pyrometry, but temperature sensing is increasingly measured by fiber optics. Generic optical access to these processes is also a common need, as is sampling, although non-intrusive sensing is the current trend. The design of sampling probes has additional design features in that the temperature of the sampled flow must be carefully controlled. In some cases the flow must be kept hot until external measurements can be done, but more often the flow must be quickly quenched thermally, adding to the probe heat sink requirements.

The chemical processing industry functions under different constraints. In this case the environment rarely consists of only the gas phase, because gas mass flows are too small to generate large amounts of product. Often the chemical conditions are harsh and there is fluid flow made up of two and three (solid/liquid/gas) phases. These flows are very difficult to diagnose externally, and can generate very high heat fluxes, as well as corrosion and erosion problems. The chemical environment, combined with temperature are crucial factors, together with probe cleanliness. The most important industrial processes are powder processing and boiling liquid; both continually spread small particles throughout the flow.

Corrosion is a pervasive and complex problem. High temperature and high pressure/stress accelerates corrosion, speeding the degradation of inserted probes. Corrosion may also be induced by stray electrical potentials and dissimilar metals. While oxidation is the most common form of high temperature corrosion, nitridation, carburization, sulfidation, etc. are also very common. Many industrial environments contain multiple types of corroding contaminants, such that empirical survival is a critical test of any shell design.

4. OVERALL DESIGN

A schematic of the shell design process is shown in Fig. 2. An ideal protective shell would be marginally larger than the probe, cheap and rugged, and have auxiliary sensing. As usual, current technology requires a variety of design compromises. The most important constraint is the heat flux to the outer shell and the temperature of the environment in which it operates. Also important are the allowable operating temperature of the protected probe, the diameters of the probe and shell, and the characteristics and constraints of the access to the environment. Specific constraints consist of the port size available and/or directness of the access, the reactivity, temperature, and time history of the environment, the period of use, the necessary reliability, and the optical requirements (excitation, collection, wavelength, noise level). Cost is also a factor, but cost is considered as a component of the facility cost, the total diagnostic cost, and the return on investment. The shell design is driven by the use to which it is put; a shell designed for imaging is often inappropriate for a sampling measurement. The total elapsed duration when useful data is retrieved using the probe shell is also not only an important consideration for convenience and maintenance but typically has the most impact on the cost of in process sensing.

5. COOLING DESIGN

There are well defined environmental temperature and heat flux regimes just as there are temperature regimes for materials design. At lower temperatures convection and conduction heat transfer dominate, whereas at higher temperatures (starting from 500-700^{o}C) radiation dominates. Conduction is a minor effect in gas cooled probe design, except at the probe base where a connection is made to the facility wall. Care must be taken that large temperature gradients are not created between the wall and the hot probe.

For a given temperature, high and low convective heat transfer regimes are defined both by the flow past the shell and the density of the flow environment. Stagnant or low velocity gas is the mildest case of heat transfer, requiring the least amount of cooling, whereas high velocity liquid is the worst case. In the case of flow-induced heat transfer, heat flux can be significantly reduced by interposing a hot outer shell separated from the cooled shell by a quiescent volume.

The heat transfer [1] to the probe shell at low temperatures will be dominated by convective heat transfer by a fluid at higher temperature flowing past the probe. A basic shell design to perform this function is shown in Fig. 4. For laminar flow, the heat transferred to a fluid from a flat plate is linearly proportional to the temperature difference, ΔT, between the fluid and the plate. The rate of heat transfer, q, and a heat flux, q/A, is

$$q/A = h(\Delta T) \tag{1}$$

Where where A is the area of heat transfer and h is the (constant) heat transfer coefficient. The heat transfer coefficient is defined experimentally in terms of a Nusselt number, Nu, a thermal conductivity, k, and a flow length, L.

$$h = Nu(k/L) \tag{2}$$

Different flow and fluid regimes are defined by the dependence of Nu on flow parameters such as Reynolds number, $Re_L = \rho uL/\mu$, and the Prandtl number, $Pr = c_p\mu/k$, where ρ is the fluid density, u is the fluid velocity, L is a characteristic length, and μ is the fluid viscosity. Many correlations give Nu for different geometries and fluids.

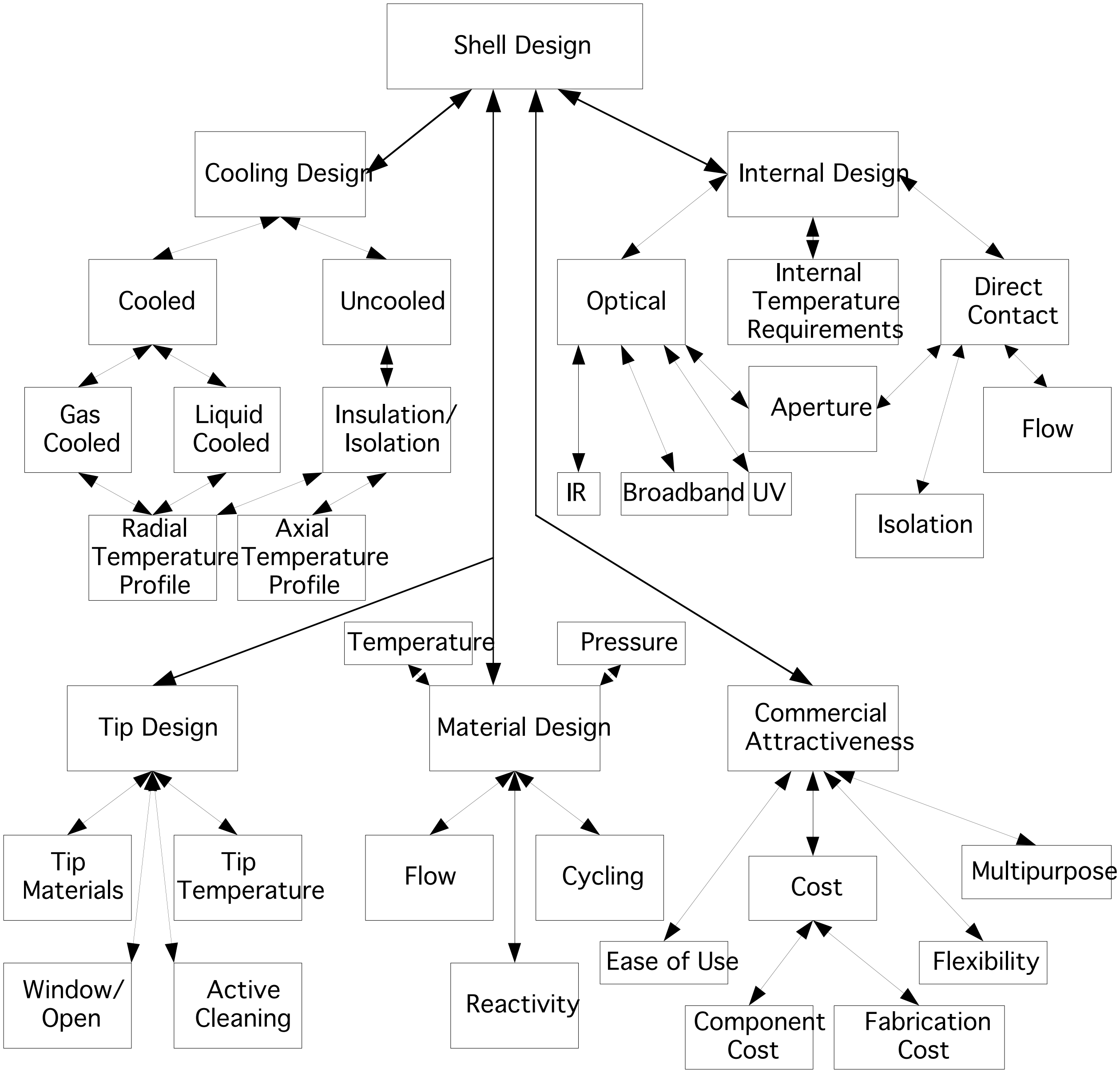


Figure 2. Endoscope design process schematic.

The heat transfer calculations performed for a gas cooled probe are complicated by growing thermal and momentum boundary layers inside the probe shells. For laminar flow the Nusselt number is:

$$\mathrm{Nu} = 0.664(\mathrm{Re}_L)^{1/2}(\mathrm{Pr})^{1/3} \qquad (3)$$

For turbulent flow the dependence of Nu changes; the Re exponent changes to 0.8 and that of Pr to 0.4.

5.1. Air/Water Cooling Comparison

Based strictly on heat transfer capability, the heat transfer capabilities of air relative to water can be compared using the data shown in Table 1. Denoting water parameters by the subscript w, and air by a, the ratio of heat transfer capabilities, R_q, is:

$$R_q = (q/A)_w/(q/A)_a = (k_w/k_a)(\mathrm{Re}_w/\mathrm{Re}_a)^{1/2}(\mathrm{Pr}_w/\mathrm{Pr}_a)^{1/3} \qquad (4)$$

On a mass basis, gases have similar specific heats to liquids. In terms of the individual varying parameters R_q is:

$$R_q = (k_w/k_a)^{2/3}\,(\rho_w u_a/\rho_w u_a)^{1/2}(\mu_a/\mu_w)^{1/6}(c_{pw}/c_{pa})^{1/3} \tag{5}$$

Substituting Table 1 values for nitrogen (air) and water at room temperature:

$$R_q = 66\,(u_f/u_h)^{1/2} \tag{6}$$

The velocity difference in the two cases has been purposely carried through, because unlike the length scales, the velocities for gas cooling can be much higher than liquid cooling. The reasons for this are that liquids have so much momentum at high speed that they can not easily be turned, and that at high velocities, liquids are very sensitive to cavitation separation from the heat transfer surfaces. Gas cooling velocities can be as much as a factor of 100 larger, which would increase the cooling capacity of helium gas to within a factor of 7 relative to water. For turbulent flow the dependence of Nu changes; the Re exponent changes to 0.8 and that of Pr to 0.4, but the overall increase in heat transfer is only about a factor of 2. If one factors in the additional safety factor required to prevent boiling, these calculations indicate that air cooling can be of comparable effectiveness to water.

Table 1. Cooling properties of water and common gases.

Property	N_2	He	Water
T_{use}(K)	300	300	300
ρ(g/cm^3)	1.15×10^{-3}	0.16×10^{-3}	1.0
k(W/m-K)	0.025	0.155	0.61
Cp(kJ/kg-K)	1.04	5.19	4.18
Pr	0.72	0.67	8
μ (μPa-s)	17.9	20	890

For gas cooling there is no such problem because in this case the heat transfer from the hot spot simply increases with the temperature difference. There is also an another effect for gas flow that stabilizes the heat transfer for global heating, as shown in Fig. 3. As the gas temperature increases, its density decreases, and since mass flow rate must be conserved, the gas must speed up, increasing heat transfer.

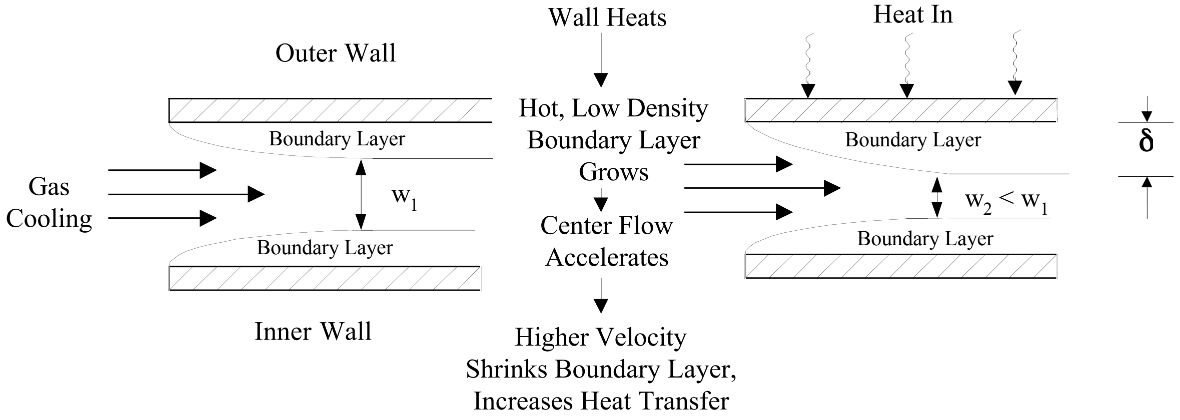


Figure 3. Schematic of tube flow gas cooling response to heating.

The heat transfer to a cooled shell is determined by the parameters describing both the external fluid and the radianting surfaces. The capacity for cooling the shell is determined by the required penetration length of the shell into the environment, the cross sectional shape of the probe, the shell outer diameter, the probe outer diameter, the flow path and turning geometry, the internal supporting structure, the pressure supplied to the cooling fluid, and to some extent the roughness of the internal surfaces.

The assumed coolant gas is air, but other gases can be used. Inert gases such as nitrogen or argon that can be recirculated can be considered in cases where oxygen will lead to corrosion of the inside surface of the outer shell. Helium is often considered as a result of its excellent heat transfer properties as a gas. Steam is also excellent as a gas coolant at higher temperatures, with the advantage of the great amounts of heat that can be removed outside the probe by condensation.

5.2. Air/Water Cooling Comparison

At high temperatures (above about 1000°C) radiant heat transfer is the dominant mechanism for heat transfer, in this case between the walls of the facility and protruding probes. Techniques that reduce radiant heat transfer are fundamentally different from convective and conductive heat transfer reduction, and require the preparation and maintenance of special surfaces that emit little radiation and reflect most radiation. The total radiated power by a blackbody at temperature, T, is given by the Stefan-Boltzmann function:

$$W_{total}(T) = 5.679 \times 10^{-12}\, T^4 \qquad \mathrm{W/cm^2} \qquad (7)$$

The T^4 dependence of the radiated power accounts for the dominance of radiation at high temperatures. For real materials the total radiated power differs from that of a blackbody by the total emittance, $e_{t.}$ Total emittances are integrals over wavelength of detailed emissivities that are also wavelength dependent. Total emittances can be quite low, but usually depend strongly on temperature, generally increasing with temperature. The theoretical descriptions of the optical constants of solid, pure materials are reasonably well known, but the optical properties of materials at high temperatures have not been extensively measured.

Radiation shielding for probe thermal protection is critical for high temperature applications, but is made difficult by the lack of efficient shielding materials that survive in high temperature oxidizing atmospheres. The most common solution is to encase the probe shell in a material that can tolerate the full environmental temperature and enclose another shell that has a low emissivity coating that operates at a much lower temperature and is encased in a protective atmosphere. This type of design is necessary for probe protection from high temperatures, but incidental to gas cooled probe design.

5.3. Specific Gas Cooled Design

The basic cooling design considered here is shown in Fig. 4, using the example of an optical probe. It consists of 3 concentric tubes; an outer tube at the end of the shell to supply and contain cleaning/tip cooling flow, an outer shell tube with a thin window sealed on the end, and an internal flow separator tube. At the center of the shell is a probe that defines the inside of the outward flow channel. The tubes are sized for enough flow for cooling. The goal of the cooling design is to maximize operating temperature for a given fluid and mass flow rate, and to eliminate any hot spots on the shell.

Quantitative estimations of the capability of air cooling for this design are as follows. Assuming room temperature air as the coolant, a tube length on the order of 50 cm, and a flow velocity of 10 m/s gives Re on the order of 10^6, not well into the flat plate turbulent regime. The laminar flow Nusselt number is then about 600 and the heat transfer coefficient, h, is about 30 $\mathrm{W/m^2\text{-}K}$. For a temperature difference of 100°C, this implies a heat flux of 0.3 $\mathrm{W/cm^2}$. This is approximately the same amount of heat that is transferred to the outside of the probe by a 1 atm pressure 500°C air flow passing at right angles over it at a speed of 1 m/s. The pressure drop needed to drive this air flow in the probe is on the order of a 10 atm, and the mass flow rate about 0.4 standard $\mathrm{m^3/min}$ (10 scfm), which is fairly easy to provide.

At higher temperatures it would be more difficult to cool with air, but still possible. At 1000°C blackbody radiation provides 15 $\mathrm{W/cm^2}$ of heat flux, which is what a black, cooled outer shell would have to absorb. This cooling would require high velocity pressurized air. However if there was an outer shell vacuum insulated from an inner tube made of a material with an emissivity of 0.1 this inner tube could be air cooled as described above fairly easily. These calculations show that air can be an effective coolant for protective probe shells, even at high temperatures. The high temperature cooling problem is greatly eased if radiation shields is used.

A critical aspect of the gas-cooled probe shells discussed here is that the gas can be used as a thermal shield rather than a coolant. For comparatively high velocity hot flows past the probe it can be shown that the cooling capacity of the air is small compared with the heat transfer to the outer shell, so that for the air "cooled" probe shown in Fig. 4 designed here, the air is actually acting as a heat transfer barrier. In this case the design constraint is that the thermal boundary layer on the outside should not reach the inside wall at the end of the flow passage. The hot layer grows faster than the cool boundary layer on the inside, and if it can be kept from contacting the inner tube, the heat transfer to the inner tube is greatly reduced. Larger passages also lead to a lower pressure drop, but a larger overall probe. The growth of the displacement thickness of a boundary layer on a flat plate is:

$$\delta_d = x\,(2/Re_x^{1/2}) \qquad (8)$$

where δ_d is the displacement thickness, x is the distance since the start of boundary layer growth, and Re_x is the Reynolds number. Room temperature air flowing on a flat plate at a velocity of 1 m/s, Re_x at 40 cm down the plate is about 2×10^4 (laminar flow), and the displacement thickness is 5 mm, which implies a reasonable tube spacing for a 3 cm diameter shell such as the shell design of Fig. 4. For room temperature air flowing at a velocity of 10 m/s, Re_x at 10 cm down the plate is about 5×10^4 (laminar flow), and the displacement thickness is 1 mm, which is approximately the appropriate boundary layer thickness needed for the design shown in Fig. 4.

For the case shown in Fig. 4, assuming a 100 m/s flow velocity and heat transfer correlations of flow past a tube, a heat transfer factor, h, of about 2 kW/m^2-K is calculated. Considering air flowing through a 2 mm wide annulus at 10 atm and 10 m/s, the mass flow rate is on the order of 0.01 kg/s, and the heat absorbed in the flow for a 100^oC warming is about 1 watt. This degree of cooling, however, coupled with the gas sheath around the probe, is adequate to reduce the probe temperature a few hundred degrees C, which will greatly aid the materials design. The pressure drop needed to drive this air flow in the probe is less than 1 atm, and easily achievable.

5.4. External Gas Flows

One way of lowering the outer shell temperature is by creating a cooler sheathing flow around the probe, supplied by gas flowing through holes in the outer shell. This type of design is already used widely for turbine blade cooling, although in this application is not cost effective to use sophisticated hole drilling techniques to provide a large number of evenly spaced cooling holes. A small number of holes can be drilled in the upstream side of the outer probe shell to provide a radial sheath flow. The hole sizing and distribution is dependent on the flow in the environment and is determined during probe testing.

Tip design is a critical part of the entire shell design and must be considered carefully. Heat fluxes tend to be highest at the tip and cooling lowest as a result of flow stagnation regions. To avoid this situation the end of the probe should be rounded and the internal flow passage radially symmetric. Two tip cleaning/cooling designs are shown in Fig. 5. A key design element is that the cleaning jets properly directed. This is done by having a long enough

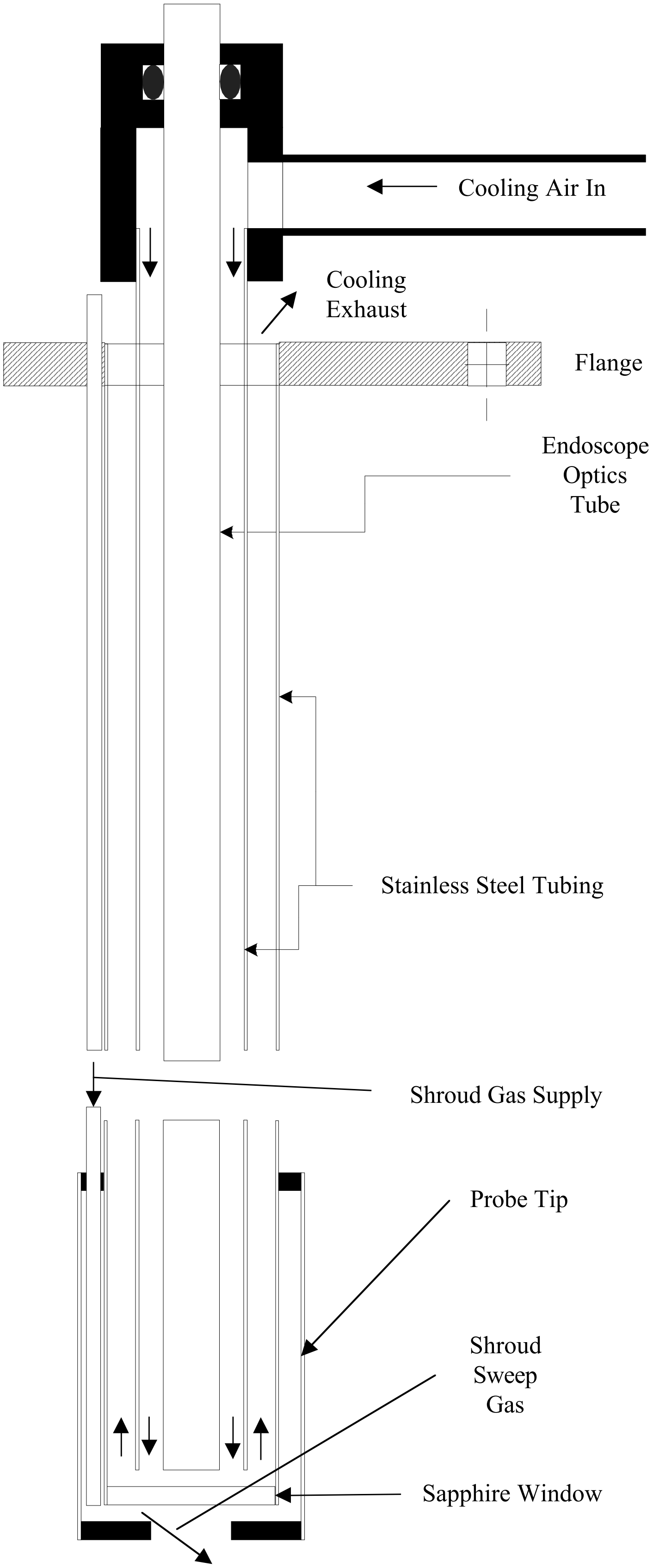
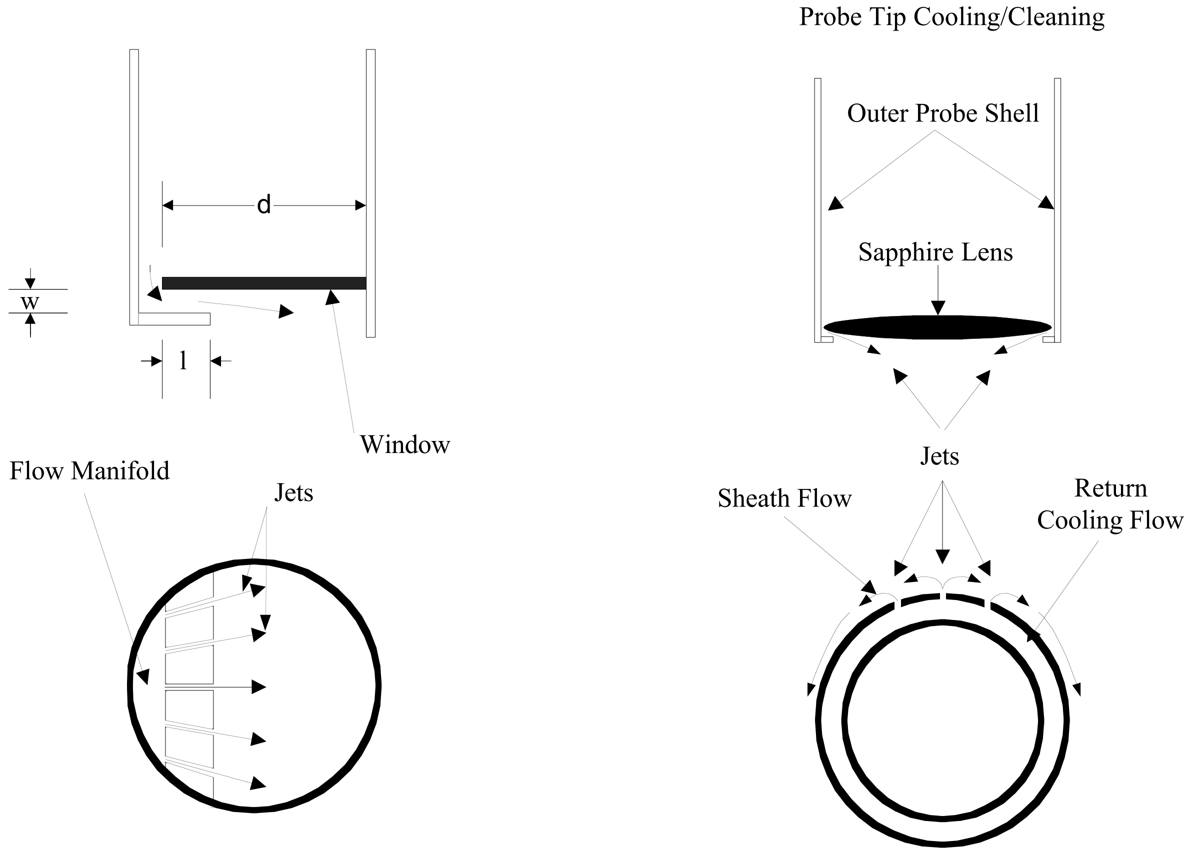


Figure 4. Endoscope cooling design schematic.

channel to turn the flow. Another key element is to keep the jet attached to the surface to be cleaned. This will tend to happen as a result of the Coanda effect if the jet is aimed close to the surface and parallel to it. The jet must also be large enough to remain coherent over the width of the window. Jets typically break up on length scales more than 10 times their diameter; this breakup length and the window diameter set a lower limit on jet diameter. Planar jets are difficult to create and control and should be avoided.

Figure 5 also shows a simple way to protect a sapphire lens. The lens is clamped into the tip of the probe with serrations in the metal edge that has been rounded over that provide flow over the lens. This does not provide good cleaning jets, but if the lens faces the flow directly, the cleaning flow can create a larger stagnation flow region in front of the lens to keep it clean.



Side Probe Tip Cleaning

Outside Sheath Cooling

Figure 5. Schematic of external gas flow cleaning and cooling geometries.

Cleaning flow, if it can be tolerated by the environment (very little flow is actually required), has the major advantage of also cooling the tip. The tips should also be designed to be modular so they can simply be welded on standard shells for improved reliability and piece turnaround in the manufacturing process.

5.5. Expansion Cooling

An actively cooled probe protector using gas flow can be made by using the expansion cooling of gas supplied from a high pressure reservoir. The motivation for this design is a significantly smaller probe shell. High pressure gas (presumably air) is supplied to the probe tip through a small diameter tube. When the pressure is applied, the end of the tube forms a sonic orifice, and the gas cools as it expands. The cold gas is then used to cool and shield the probe as it returns down the length of the probe. Expansion of an ideal gas from 50 atm supplies gas at 100 K. An air mass flow of 1 g/min supplies about 3 W of cooling power, and a standard gas cylinder will supply on the order of 10 hrs of flow to the system at these flow rates. A 30 cm long, 0.6 cm diameter gold coated probe with an emissivity of 1% in an 800^{o}C will absorb (1%)(7 W/cm^2)(60 cm^2), or about 4 watts of power. This means that a typical gas cylinder can be used to maintain a small standard endoscope at room temperature for a working day, a simple technique for probe protection for short term testing.

6. MATERIALS DESIGN

Tremendous amounts of work have been done to find materials that will survive harsh conditions. High temperature metals have been developed for aircraft turbines, combustors, and rocket combustion chambers and nozzles. High temperature ceramics are extensively used for furnaces and flame shields. Many of these applications use expensive and exotic materials that may be impractical for use in thin-walled tubes or for low volume and moderate value applications such as probe shells.

The material that will interface with the environment will, of course, be the crucial choice. For oxidation resistance at lower temperature there is an entire hierarchy of standard metals in use today, and at higher temperatures a variety of ceramics are commercially available. A rough summation of hot air resistant metals is: carbon steel is used up to 650^{o}C, Cr-Mo steel alloys at somewhat higher temperatures because of their higher strength, stainless steels are used up to 1000^{o}C, and nickel alloys and superalloys can be used for limited periods up to 1200^{o}C. Most of the high temperature alloys rely on a chromium oxide scale for oxidation protection, and this scale begins to lose its protection capabilities in the range 1000-1100^{o}C. At high temperatures, ceramics such as alumina and zirconia are commonly used, and have effective temperature limits up to 2000^{o}C. These materials are typical of ceramics in that they are difficult to form and machine. Metal shells have a higher thermal conductivity (easier to cool) but a lower use temperature, whereas ceramics are generally more expensive to fabricate. Ceramic shells are more appropriate for uncooled designs at high temperature. Stainless steels are generally chosen for long term intermittent use.

Specialized coatings can provide the protection of oxide layers to base metals. In some sense the oxide protective layer that forms naturally on many metals is already a coating, but applied oxide coatings can have some structural integrity that the naturally formed coatings do not have. If these coatings have adequate adhesion and matched thermal expansion they can, in principal, allow metals to be used at much higher temperatures in oxidizing atmospheres. A number of simple solvent based, spray-on and cure coatings (Alfa Aesar - Al_2O_3, yttria, zirconia, BN, and TiN) have recently become available. A wide variety of plasma spray and vapor deposited coatings are also available. The generic problem of this type of coating is that the coating has a different coefficient of thermal expansion than the substrate, and will tend to spall off after multiple cycling to high temperature. The coatings are most useful under oxidative, high heat flux, but relatively low temperature conditions. This is the case for the outer shell of cooled probe protectors.

7. THE OPTICAL SHELL

An optical shell consists of a corrosion resistant body sealed to a window at the end of the shell. In this case the shell material not only has to survive the environmental constraints, it must be compatible with the thermal expansion of the window and the joining/sealing technique used to attach the window to the probe body.

The choice of possible window materials is much more restricted than the choice of shell materials. The candidates are sapphire, quartz, diamond, and zirconia. Sapphire is the best of these materials in that it combines high temperature stability (melts at 2050^{o}C), almost total lack of reactivity, and good strength. It's primary drawback is its large thermal conductivity and thermal expansion, making it subject to high thermal stresses if temperatures across the piece are not properly controlled. Quartz/fused silica is the next most attractive material, and can be used at temperatures over 1400^{o}C with care. It's main drawback is its mechanical strength, less than 1/10 that of sapphire, and it is sensitive to chemical attack at higher temperatures. Diamond is strong and unreactive at lower temperatures, but is an expensive, metastable material, transforming quickly to graphite at temperatures over 1000^{o}C and burning readily in oxidizing atmospheres. Zirconia would form an excellent high temperature material if it could be grown in large enough sizes.

Many optical sensing applications require broadband infrared (IR) access, especially for thermal optical sensing. This is a much more difficult requirement to satisfy in high temperature environments because good IR materials with a wide transmission bandwidth do not tolerate even comparatively moderate temperatures, and most of the commonly used materials are more or less hygroscopic. Sapphire transmits to 5 or 6 microns wavelength, and in special cases beyond 8 microns, quartz transmits to 4 microns, and diamond transmits throughout the bandwidth, except for a gap from 3-5 microns. Infrared spectroscopy requires different materials that will have to be carefully protected by some sort of shell.

For most applications sapphire is the window material of choice. The primary issues for using small pieces of sapphire at very high temperatures concern techniques for sealing it to the probe body and its optical transmission properties. Its survival in terms of strength is less important because of its small size, at least up to temperatures in excess of 1800°C. At these temperatures sapphire becomes increasingly plastic before it melts just above 2000°C. It also becomes increasingly opaque at temperatures above 1500°C.

7.1. Window Sealing Design

One critical aspect of including a window in a probe shell is the need for a seal that can operate at high temperature and be cycled to room temperature many times. Standard brazed designs are rated above 600°C for many cycles. Brazing techniques are available for higher temperatures, but the lifetime of the window in terms of survived cycles is dramatically reduced based on current techniques. Using sapphire that has its c-axis aligned with the probe axis appears to be critical in order to avoid non-uniform expansion. For brazing, materials with graded indices of expansion are used, together with some degree of yield. Precious metal brazing has been successfully used beyond 1000°C.

The next higher temperature sealing regime that is accessible for sapphire windows involves the use of probe tips that are either wholly made out of sapphire, or made out of alumina tubes with a sapphire window attached. The sapphire/alumina tubes extend far enough away from the hot zone to be able to join them to a metal base with conventional brazing technology. There are a number of temperature regimes for the sapphire/alumina tips. The highest temperature option is to use diffusion bonded sapphire, where a thin sapphire window is attached to a tube end. This technology is practical and survives temperatures similar to sapphire itself, but is of limited application because of the expense of the sapphire. At temperatures up to perhaps 1500°C a other joining technologies can be used. A glass frit can be used to bond sapphire to sapphire or alumina to alumina. Metal seals have been demonstrated by author to join sapphire to alumina.

Another key aspect of the design is the thermal isolation design of a window, because sapphire is susceptible to thermal stress. This weakness is exacerbated by the common design of a window clamped to a cold facility wall. In this case the edge of the sapphire is cold and the center is hot - causing high thermal stress, window failure, and a bad reputation for sapphire. Proper design thermally isolates the sapphire window or the window fixture, so that the sapphire heats up uniformly and is not subject to thermal stress. This type of design must tolerate the thermal cycling, but this problem can be overcome, whereas the strength limit of sapphire cannot.

7.2. Shell Fabrication.

The overall material thickness of the tube walls are designed to maintain sufficient strength to function as a shell under loads typical of a long shell cantilevered at right angles from a vertical wall. For a multitube cooled design the need for concentric shells to provide a supply and return for cooling flows is used to advantage to support the overall structure. The inner, protected and cooled tube can be used to provide the mechanical strength for the shell while the outer corroding tube can simply function as a protective skin that only needs to support internal pressure forces.

A critical fabrication element is the joint between the window and the outer shell. Failure testing must be performed under the appropriate environmental conditions, but in most cases minor leaks are acceptable, which is not the case with water cooled probes. Thermal cycling failure is the most common problem, and is also very sensitive to absolute size, since the forces approach material strength for larger diameter (2 cm) probes. Thermocouples can measure joint temperature; the appearance of stress cracks at the periphery of the window will indicate borderline conditions.

8. TESTING

Tests have been done on the specific probe design shown in Fig. 4. The OD of this probe (without cleaning shroud, just window tube) is 2.5 cm. At a flow rate of 23 slpm (standard liters/min; 50 scfh) the tip of a 9.5 mm diameter central probe reaches 100°C for a probe external temperature of 500°C when the probe was inserted vertically 15 cm into a tube furnace hot zone and sealed with insulation at the top of the furnace. This is a low flow rate; increasing the flow to 38 slpm drops the probe tip temperature to 70°C. The probe shell showed no sign of degradation at all.

Probe survival is assessed by visual and microscopic study of the surface to look for degradation. If, as is usual, the degradation is non-uniform, the most corroded spots are examined to assess the damage level to the shell. High temperature is a concern not only in terms of the survival of the materials at these temperatures, but also through the effects of large temperature gradients and thermal cycling. Internal and external temperatures will be monitored, as well as the effectiveness of cooling, if used.

9. CONCLUSIONS

The design and development of gas cooled protective shells for standard probes has been described. The use of protective shells greatly expands the applications of a wide variety of sensing techniques for process control, and allows cost effective, safe, and simple upgrades for probes already in use. At present, water cooled probes are used almost exclusively in industry, but these cold probes perturb their thermal environment and are subject to catastrophic failure not only of the probe, but of the entire facility. Gas flows in a protective shell both cool the probe and isolate it from external heat sources, providing almost as much cooling capacity as with water. Gas flows can also supply external flows to actively cool and clean the optical tip of the probe.

High temperature window/body sealing procedures are critical for the successful fabrication of optical probes. Sapphire windows brazed onto metal or ceramic outer shells can tolerate temperatures beyond 1500^{o}C and almost any type of chemical or physical environment.

A gas cooled probe protector with a sapphire window was fabricated and tested in a furnace. The 2.5 cm OD gas cooled shell was able to keep the tip of a 9.5 mm OD internal probe at 100^{o}C using only 50 scfh of air flow when the assembly was placed 15 cm into a furnace operating at 500^{o}C. This flow was easily supplied by a small air compressor through long air lines. Post test inspection showed that the probe shell was not damaged in any way.

REFERENCES

1. W.M. Rohsenow, and H. Choi, *Heat Mass and Momentum Transfer,* Prentice Hall, New York, 1961.