PROLONGING OFF GAS DUCT LIFE WITH SPRAY-COOLING

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INTRODUCTION

Spray-Cooled Ducts utilize water at atmospheric pressure for cooling. Since the cooling system is not pressurized, high volume water leaks due to high pressure are eliminated. Nozzles that create turbulence through droplet impingement optimize heat transfer rates at any flow rate. An independent, enclosed cooling circuit provides the ability to vary the cooling capacity of the system according to localized demands. Thin-walled construction and a prescription assembly lessen the impact of thermal induced stress fatigue cracking. Shell construction combined with the separate cooling circuit promotes low cost maintainability.

This paper discusses the various features of Spray-Cooled Ducts and how their design reduces furnace downtime by prolonging duct life.

DISCUSSION TOPICS

PROCESS FEATURES

SHELL CONSTRUCTION

SPRAY SYSTEM

COOLING WATER

PIPING AND INSTRUMENTATION

MAINTENANCE AND REPAIR

PROCESS FEATURES

Spray cooling performs the cooling function at atmospheric pressure utilizing spray nozzles to supply cooling water to the duct. Nozzles are located and sized to provide the required amount of cooling water for the varying heat load areas identified in the duct. The series of overlapping sprays create a high degree of turbulence at low (atmospheric) pressure. The greater the turbulence, the more efficient the system cools. The heat transfer coefficient for turbulent flow is ten times greater than the heat transfer coefficient for laminar flow.

The benefits of spray cooling include:

- Operation at atmospheric pressure reduces the amount of water that escapes the duct enclosure when there is a leak. A typical spray-cooled furnace component operating at 3 gallons per minute per square foot would dispense only 2.5 gallons per hour through a 2 square inch hole. In contrast, a typical tubular water-cooled furnace component operating at 60 psi would discharge more than 16,000 gallons per hour through the same size hole.

- Usage of cooling water is kept efficient by distributing it according to the requirements of the varying heat load areas identified throughout the duct; less water per square foot being required in cooler areas and more water per square foot being required in hot spots. Distribution of cooling water within the duct is via stainless steel piping that is not a part of the heated surface. Fouling of the water-cooled distribution piping, which can adversely affect the heat transfer rates in tubular water-cooled ducts, is not a factor with spray cooling. Cooling water is distributed throughout the duct at the same inlet water temperature. Cooling remains constant.

- Lower water volumes at lower pressures reduce pumping costs. Pumping the same volume of cooling water at one-half the pressure reduces pumping costs by 50%. Pumping one-half the volume of water at one-half the pressure reduces pumping costs by 75%.

- Thin-walled plate construction of the independent inner shell utilizing minimal welds, rounded corners and mechanical forming make the duct less susceptible to thermal induced stress fatigue cracking. Plate construction enables repairs to be made from the outside, rather than the inside. Operation at atmospheric pressure permits leaks to be temporarily repaired by an easy "weld-a-patch" technique with the duct still in service. Permanent repairs can be scheduled around production needs.

These benefits equate to reduced furnace downtime due to improved equipment availability.

SHELL CONSTRUCTION

Spray-Cooled Ducts are typically assemblies of obround (Figure 1) or cylindrical sections. Sectioning assists in the control of accumulative water, which cascades along the inner shell bound by surface tension. Shipping and installation are also benefactors of the section approach. Each section consists of an inner and outer shell. The inner shell is the hot plate and is in direct contact with the furnace off-gas. The outer shell surrounds the inner shell forming an annular enclosure. At each end is a closure piece that connects the inner shell to the outer shell. The annulus between the two shells is referred to as the spray chamber. Access to the spray chamber is through easy-opening hatches located on the outer shell. Hatches allow inspection of the spray system and inner shell and are positioned strategically near identified hot spots.

The outer shell is the structural component of the Spray-Cooled Duct. It carries the load of the duct and is to which all supports are attached. The outer shell provides support to the inner shell by attachment only at the ends. Since the enclosure is vented and operates at atmospheric pressure, no additional connections between the inner and outer shell are required. This construction provides the minimal amount of constraint on the inner shell, which undergoes cyclic thermal expansion and contraction. Combined with plate thickness optimized based on heat load, this feature serves to minimize thermal stress fatigue cracking.

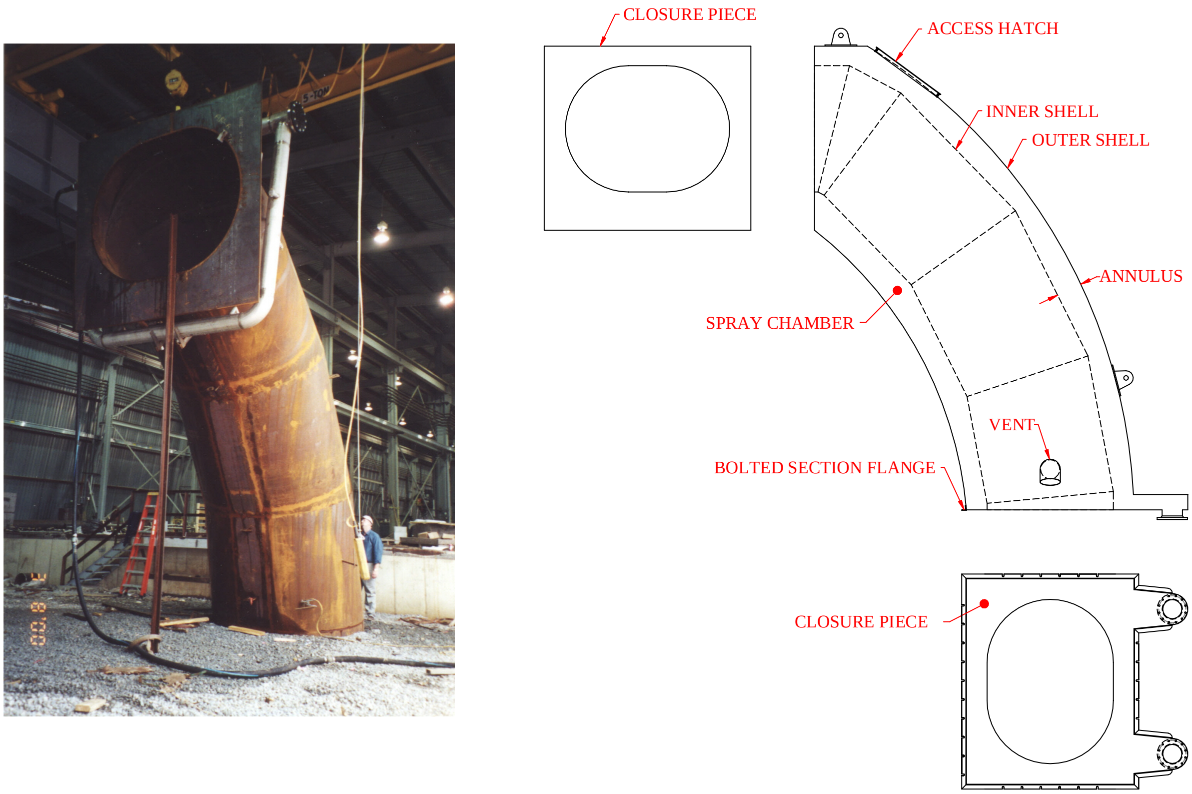


Figure 1

The primary material used for the inner shell in Spray-Cooled Equipment is carbon steel, pressure vessel quality ASTM A-516 Grade 70 plate. Properties such as thermal conductivity, allowable stress, workability and cost effectiveness have demonstrated that, for most applications, carbon steel suitable for use at elevated temperatures is preferred.

Thickness of the inner shell is a function of two considerations. One thickness will be considered based on its effectiveness in minimizing thermal stress fatigue cracking. Another thickness will be considered based on its effectiveness in resisting corrosion and wear. Following is a sample determination of the proper material thickness considerate of heat load and thermal stress:

GIVEN INFORMATION:

- Existing duct cooling water flow rate = 3000 gpm
- Water temperature in = 80°F
- Water temperature out = 160°F
- Surface area = 617 ft^2
- Plate Coefficient of Thermal Expansion = 6.33 x 10^{-6} in / in x °F
- Plate Modulus of Elasticity = 30 x 10^6 lb / in^2
- Plate Poisson’s Ratio = 0.303
- Plate Thermal Conductivity = 25 Btu/hr x ft x °F

ANALYSIS:

$$\text{Heat Flux} = \frac{\text{Mass Flow Rate x Specific Heat x Delta Temperature}}{\text{Area}}$$

$$\text{Plate Differential Temperature} = \frac{\text{Heat Flux x Plate Thickness}}{\text{Plate Thermal Conductivity}}$$

$$\text{Stress} = \frac{\text{Plate Coefficient of Thermal Expansion x Plate Modulus of Elasticity x PlateDifferentialTemperature}}{\text{2 x (1-Plate Poisson's Ratio)}}$$

Combining the last two equations produces the following relationship:

$$\text{Stress} = \frac{\text{Plate Coefficient of Thermal Expansion x Plate Modulus of Elasticity x Heat Flux x Plate Thickness}}{\text{2 x (1-Plate Poisson's Ratio) x Plate Thermal Conductivity}}$$

HEAT FLUX:

$$\text{Heat Flux} = \frac{\text{3000 gal/min x 8.33 lb/gal x 60 min/hr x 1 Btu/lb x °F x 80°F}}{617\ \text{ft}^2}$$

Heat Flux = 194,490 Btu/hr x ft^2

STRESS:

$$\text{(For 0.50" Plate) Stress} = \frac{6.33 \text{ x } 10^{-6}\ \text{in/in x °F x } 30 \text{ x } 10^{6}\ \text{lb/in}^2 \text{ x 194,490 Btu/hr x ft}^2 \text{ x 0.50/12 ft}}{\text{2 x (1-0.303) x 25 Btu/hr x ft x °F}}$$

Stress = 44,158 lb/in^2

$$\text{(For 0.375" Plate) Stress} = \frac{6.33 \text{ x } 10^{-6} \text{ in/in x °F x } 30 \text{ x } 10^{6} \text{ lb/in}^{2} \text{ x } 194{,}490 \text{ Btu/hr x ft}^{2} \text{ x } 0.375/12 \text{ ft}}{2 \text{ x } (1-0.303) \text{ x } 25 \text{ Btu/hr x ft x °F}}$$

Stress = 33,118 lb/in^2

$$\text{(For 0.25" Plate) Stress} = \frac{6.33 \text{ x } 10^{-6} \text{ in/in x °F x } 30 \text{ x } 10^{6} \text{ lb/in}^{2} \text{ x } 194{,}490 \text{ Btu/hr x ft}^{2} \text{ x } 0.25/12 \text{ ft}}{2 \text{ x } (1-0.303) \text{ x } 25 \text{ Btu/hr x ft x °F}}$$

Stress = 22,079 lb/in^2

FATIGUE:

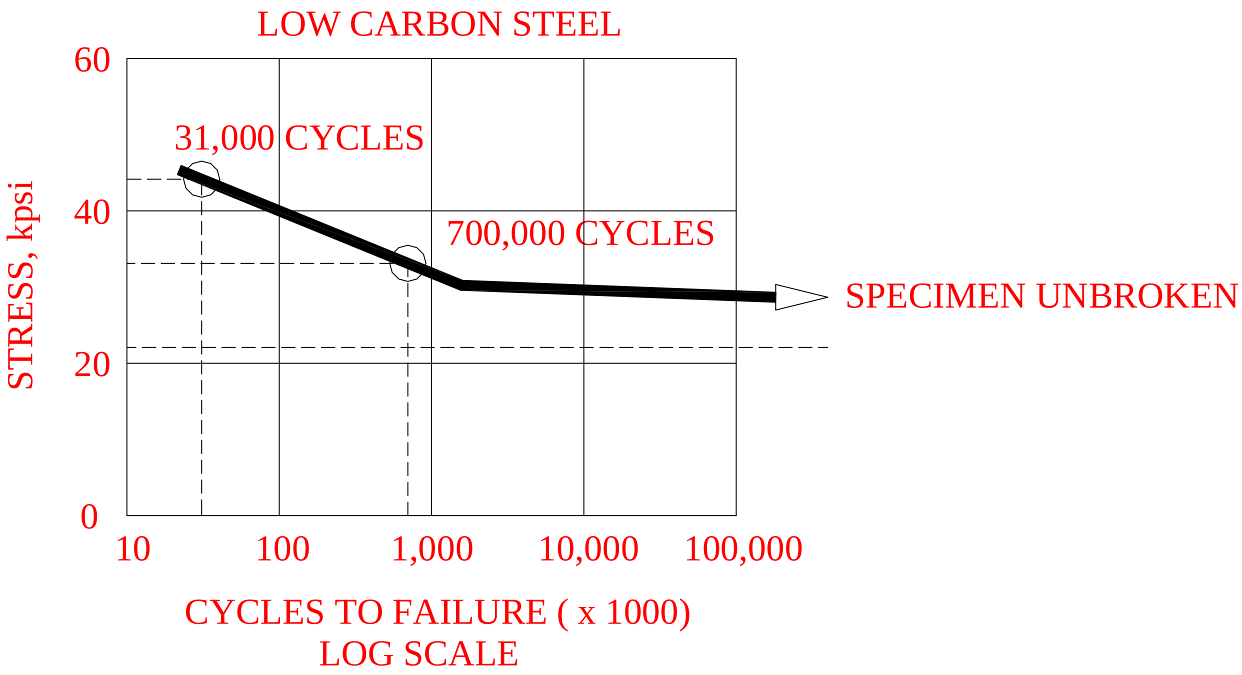


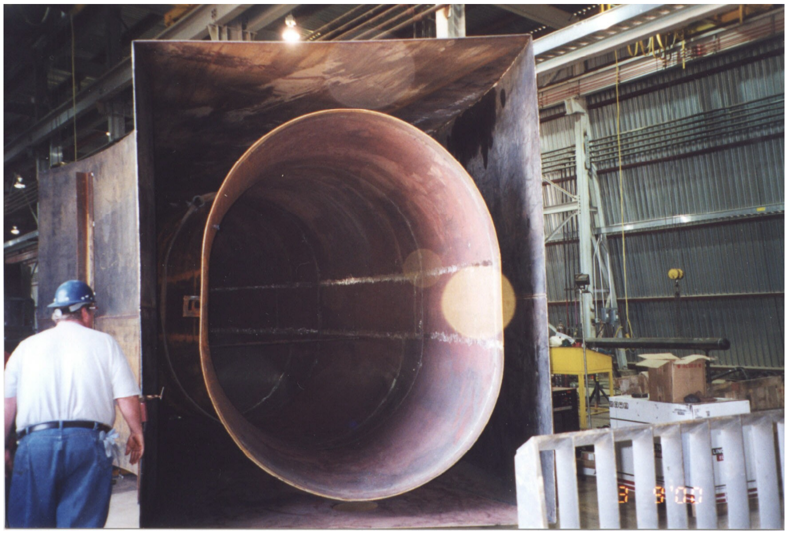
Figure 2

From Figure 2, the cycles to failure for the sample with a 0.50” thick inner shell is approximately 31,000 cycles. The cycles to failure for the sample with a 0.375” thick inner shell is approximately 700,000 cycles. A 0.25” thick inner shell would have a fatigue life that would exceed 100 million cycles. If based solely on fatigue life expectancy, the proper thickness for the carbon steel inner shell would be 0.25”.

Typically, off gas duct gas streams are directed through relatively sharp bends enroute to emissions control equipment. Requisite high emissions draft rates increase the amount of particles that become entrained in the gas stream. These particles initiate erosion that is intensified by the sharp gas stream directional changes and the topography of the common tubular water-cooled ducts. Compounding this, corrosion caused by deposition of aggressive gas stream components (dilute sulfuric acid accumulations on slag particles or entrapped hydrochloric acid concentrations) can result in the formation of oxide scales. Oxidation, and the repetitive formation and removal of the oxide scales by erosion can accelerate metal removal or thinning of the exposed surface. This process can have a negative effect on the fatigue life of the duct as this chemical/physical attack can accelerate crack propagation and effectively reduce the number of cycles to fatigue failure. Except for the miter joint directional changes used in the construction of the spray-cooled duct inner shell, the exposed surface of the spray-cooled duct is smooth and presents free passage to the gas stream. The miter joint weld seams are ground smooth on the exposed surface and provide no crevices for the accumulation of corrosion causing gas stream components. However, if corrosion or erosion wear is identified as the mode of failure, life can be extended proportional to an increase in plate thickness. Doubling the inner shell thickness would double the wear life expectancy. Shell thickness though, should be optimized for wear considerate of an acceptable fatigue life expectancy.

Fatigue and wear life are built into the spray-cooled duct with the proper selection of inner shell plate thickness. Shell design must also take into account the effects of welded corners. Corners present a point of high potential for thermal stress fatigue cracking. They should be allowed to expand and contract freely by being unrestrained by their geometry or by nearby welds, reinforcements or attachments. Chamfering is an effective means of minimizing stress concentration at corners.

Prescription plate construction and assembly are parts of a successful recipe for improved maintainability that prolongs off gas duct life.



SPRAY SYSTEM

The spray system (Figure 3) is an arrangement of noncorrosive piping and nozzles. Spray nozzles are typically removable by means of detachable spray bars that connect to a water supply header. A single inlet feeds the header. The entire piping network is attached to the outer shell so that the inner shell may be replaced without affecting the spray system.

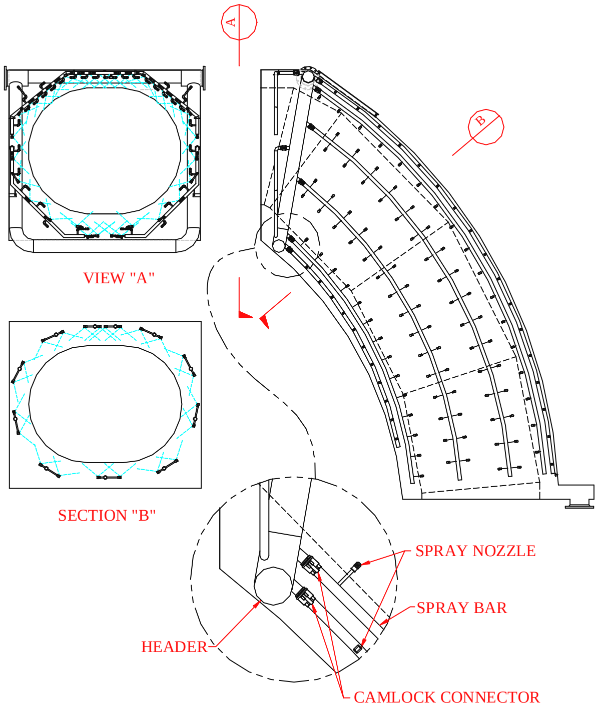
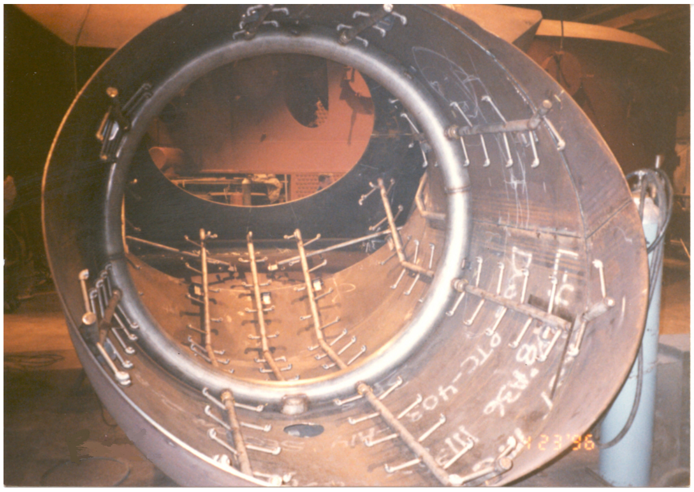


Figure 3



The amount of water distributed in a particular area of the duct is determined by the size of the nozzle used, the quantity of nozzles and the pressure at which the water is supplied. The resulting water distribution (gpm/ft^2) affects the system efficiency and reliability.

Droplet impingement produced by the spray nozzles rather than water velocity typical for pressurized tubular cooling provides the turbulence required for optimal heat transfer. Very effective heat transfer is thereby obtained at virtually any flow rate. Cooling water is distributed according to the varying heat load demands identified in the duct; cool spots – less water, hot spots – more water. Available water is used most efficiently.

Cooling capacity can also be readily increased. Camlock connectors facilitate spray bar removal. Either replacing existing nozzles with larger capacity nozzles or adding more nozzles will supply additional water and corresponding cooling.

Spray nozzles are available in a variety of capacities and spray angles. The nozzles most commonly employed in spray-cooled equipment today range in capacity between 2.6 and 7.0 gpm per nozzle @ 30 psig and have a 110° full cone spray pattern. To accommodate placement of the piping network a 12-inch annulus is preferred. Nozzle spray angle, nozzle capacity and the distance the nozzle is away from the spray-cooled surface determine the cooling water flow rate per unit area (gpm/ft^2) and the amount of overlapping coverage. Figure 4 shows the effect of nozzle distance away from the spray-cooled surface.

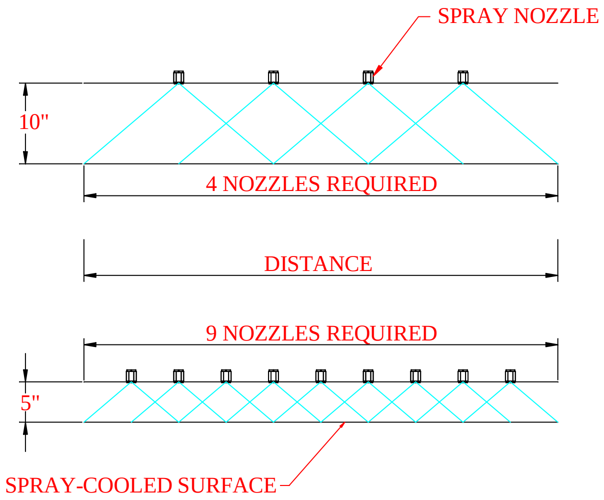


Figure 4

COOLING WATER

Heat loads dictate the cooling water requirements for spray-cooled equipment. The amount of water required is inversely proportional to the allowable water temperature rise between the inlet and outlet of a particular section for an identified heat load. Lower water temperature rises require usage of higher volumes of cooling water. Higher water temperature rises permit usage of lower volumes of cooling water.

There is however, a limitation that must also be observed. Cooling water must be supplied at a rate sufficient to minimize film boiling. Evaporative cooling is undesirable. Boiling begins as water on the heated surface is superheated slightly, and subsequently evaporates. Bubbles begin to form on the surface during nucleate boiling. As the temperature continues to rise, rapidly forming bubbles blind the heated surface preventing replenishment with fresh liquid. A vapor film, which covers the surface, forms as the bubbles coalesce. Heat must then be conducted through the film before it can again be exposed to the cooling water. This thermal resistance causes a reduction in heat transfer and conditions become very unstable. Film boiling occurs. The surface must dissipate the applied heat flux, or its temperature will rise catastrophically above the melting temperature of the metal. For this reason, outlet temperatures are limited to at or around 160°F ensuring that sufficient cooling water is available for the normal heat flux and providing ample margin to accommodate transient heat loads. Nozzle spray pattern overlap provides additional protection against this phenomenon. Should a nozzle somehow become restricted, adjacent nozzles will provide back-up cooling to the affected area.

Accumulative run-off water forms a cascading film that bonds to the inner shell by surface tension and flows along the shell to assist the cooling process by offering reserve cooling capacity.

COOLING WATER QUALITY

Water quality requirements are comparable to the requirements of water used in other water-cooled equipment throughout the plant. Keeping water temperatures low and distributing the water through noncorrosive piping lessens water quality requirements. Water with a **ph**, which is neutral to slightly alkaline (7 to 8), has **Total Hardness** not greater than 200 ppm, has an **Alkalinity** not greater than 150 ppm, has **Total Dissolved Solids** not greater than 400 ppm, has **Largest Particulate Size** not greater than 0.030 in. and at a **Temperature** not greater than 110°F is optimal.

Properly functioning spray nozzles are a key factor in the successful operation of spray-cooled equipment. Nozzle blockage is minimized by the installation of a mechanical strainer through which all cooling water must pass in route to the duct inlet. A strainer screen opening of 1/32” maximum is recommended.

SUPPLY WATER SYSTEM PIPING AND INSTRUMENTATION

Cooling water is supplied to a Spray-Cooled Duct through noncorrosive piping circuits as simplified in Figure 5. A supply line carries water to the duct location. From there, a header distributes water to the duct section(s). Each section has a single inlet with its respective flow control valve. A strainer, typically common to all sections, is installed in the proximity of the duct. Noncorrosive piping downstream of the strainer ensures against rust contamination. A flow measurement device located between the strainer and the section is used to monitor low and high flow conditions. Temperature sensors located at the discharge outlet of each section monitor discharge water temperature. The flow and temperature monitors are connected to an alarm panel or PLC.

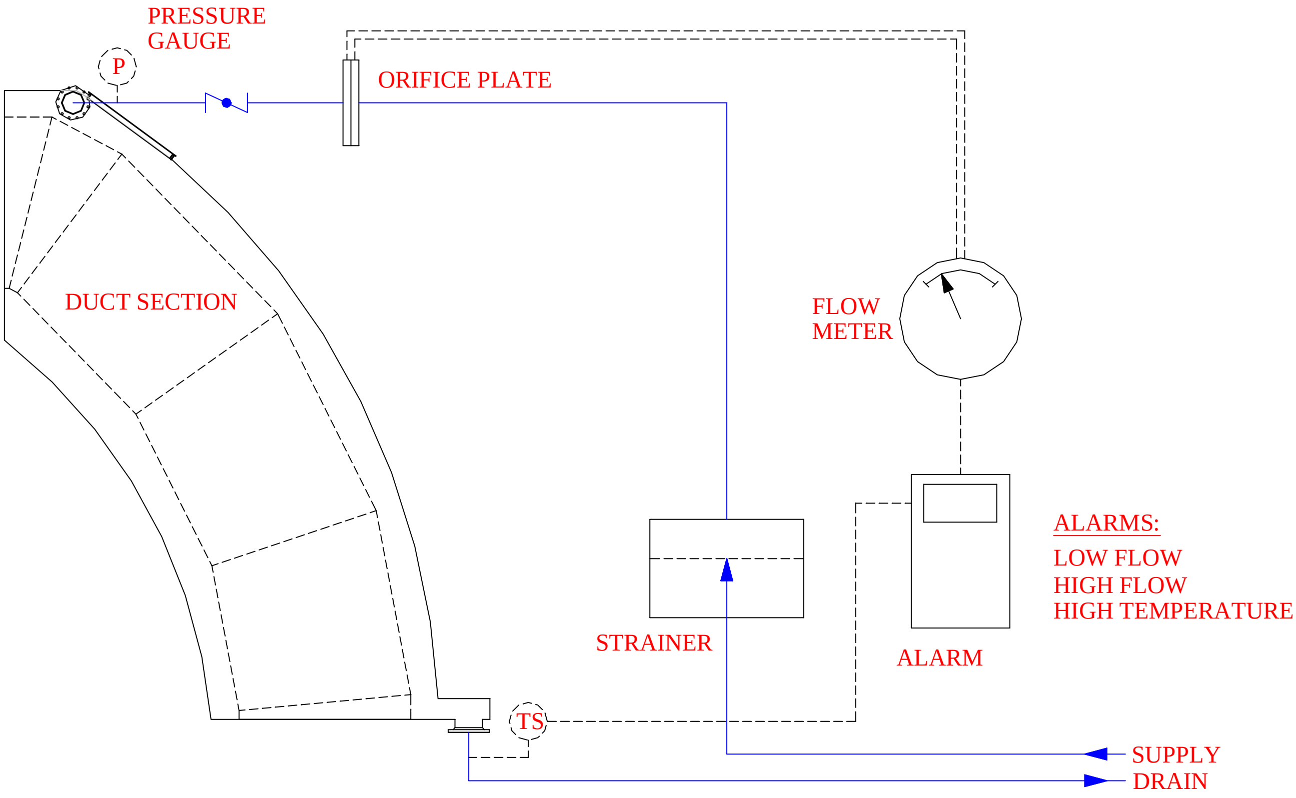


Figure 5

INSPECTION

Daily maintenance should not be required. Periodic inspection should be done to ensure proper operation of the cooling system. A visual inspection of the spray chamber and verification that flow and temperature monitoring equipment are functioning properly should be sufficient.

Visual inspection of the spray chamber requires access during a time when cooling water flow can be reduced. Visibility is increased as the flow rate is reduced. An inspection confirms that nozzle spray patterns are uniform with no signs of blockage and that the condition of the inner shell is normal. New spray nozzle designs, with larger passages that are less likely to become blocked, have reduced the need to inspect the spray patterns.

REPAIR

Should a crack or hole be discovered in the inner shell, the amount of water leakage would be minimal. For this reason, most inner shell repairs can be scheduled during a planned shutdown.

Repairs can be made from the outside of the duct. Temporary repairs involving welding up a crack or installing a patch over a hole is an inherent advantage of spray cooling and is recommended to maintain operations until a scheduled shutdown. The inner shell is accessible by cutting an opening in the outer shell. The incident area is prepared by removing the damaged plate material to a minimum distance larger than the hole or back to original thickness plate whichever is the greater. Then a patch plate of similar thickness carbon steel, which overlaps the prepared cut out, is welded in place with a full circumferential fillet weld. Permanent repairs can be made on a down day when time will permit removal and replacement of the damaged area. Preparation of the incident area is the same. More care is taken that the patch be prepared from the same thickness material and grade of steel recommended for a permanent hot plate repair. The patch plate is installed flush with the existing plate with the edges of both the new plate and existing plate prepared for a full penetration weld and finish.

Spray-Cooled Ducts are designed for maintainability. The inner shell eventually wears out but can be replaced in whole or part. Since there are no attachments from the outer shell or spray system to the inner shell other than the end connections, replacement is quick and inexpensive. The inner shell is simply cut free by removing the weld at the closure piece ends. Once free, the old inner shell is slid out and a new inner shell is slid in and welded to the closure piece ends. The outer shell and spray system, allowing for normal wear and tear, should last indefinitely.

CONCLUSION

A Spray-Cooled Duct has inherent features that minimize many of the problems typical of pressurized tubular ducts. As previously discussed, high pressure, high volume water leaks, unmanageable thermal stress fatigue cracking and difficult and/or expensive maintenance are a few areas where spray cooling provides appreciative improvement.

In summary, the primary advantages of spray-cooling over conventional pressurized cooling are the elimination of the source of high pressure, high volume water leaks; the ability to effectively transfer heat at low flow rates; the consistency and uniformity at which cooling water is distributed; the ease at which cooling water distribution can be matched to duct requirements; construction that lessens the impact of thermal induced stress fatigue cracking; and a complete assembly that promotes life prolonging maintainability.

This discussion described the features of spray cooling that prolong fixed duct life. These and other benefits can be substantiated by years of consistently good performance in electric arc, basic oxygen and argon-oxygen decarburization furnace steel making.

Systems Spray-Cooled Technology is covered by one or more patents – United States Patent Nos. 4,715,042; 4,813,055; 4,815,096; 4,849,987; 5,115,194; 5,330,161; 5,327,453; 5,444,734; 5,561,685; 5,648,981 and foreign patents.

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