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Installation and Experience Using a Systems Spray-Cooled EAF Roof

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ABSTRACT

A leading steel foundry in Ohio, successfully installed and commissioned a new spray-cooled roof to replace their existing refractory brick roof in 2008. The conversion from refractory to spray-cooling was done to reduce the refractory and maintenance costs associated with a brick roof and to increase the availability and safety of their 20-ton electric arc furnace (EAF). This paper will describe the project as well as the plant's 16 years of experience with the operation and maintenance of spray-cooled equipment.

Keywords: refractory, roof, spray cooling, safety, maintenance, efficiency, engineering, electric arc furnace, EAF, foundry

INTRODUCTION

In 2008, the Midwest plant installed one (1) 12.5ft. (3.8m) diameter spray-cooled EAF roof, replacing their refractory brick roof on EAF #2. A spare was not purchased at that time in hopes that it would be ordered in the future. The spray-cooled roof was removed from service in 2019 due to severe arcing damage and warpage As a spare roof was never ordered, a cast refractory roof was reinstalled. In late 2021, a new improved design spray-cooled roof was installed. This paper will review the original reasons for replacing the refractory roof and the results of the spray-cooled roof. The changes and improvements that were made along the way, including maintenance costs, equipment lifetime, and safety will also be discussed.

The Ohio facility is capable of producing several hundred thousand tons of steel per year. The complex currently operates (2) 20 ton EAF's.

HISTORY OF SPRAY COOLING

The first commercial spray-cooled piece of equipment, an EAF roof, was installed at the Timken Steel Harrison Plant in Canton, Ohio, in 1986. The 20.5ft (6.2m) diameter roof was in operation until the plant was idled in 2021 (Figure 1).

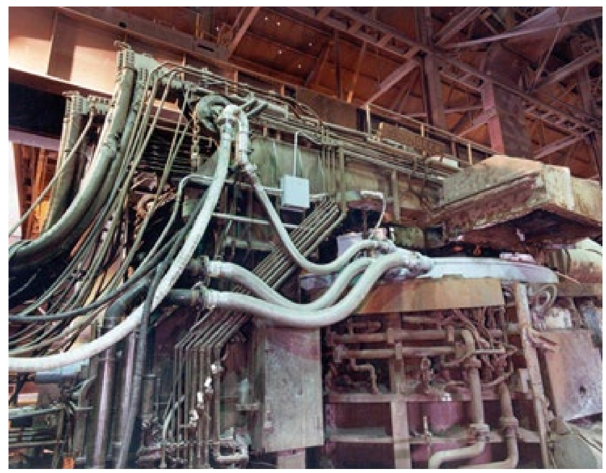

Figure 1. This photo shows the original spray-cooled EAF roof commissioned in 1986.

The technology has evolved and grown over the years through continuous improvement and new developments to handle a wide range of cooling applications and requirements. Spray cooling is now used on over 100 furnaces and has been installed in 20 countries worldwide.

SCIENCE BEHIND SPRAY COOLING

Spray cooling is an alternative cooling approach to brick/refractory systems and conventional high-pressure tubular piping systems. Spray-cooled equipment operates at atmospheric pressure. The cooling water is supplied at a pressure between 30 psi to 40 psi (2.5 bar) as compared to 75 psi (5 bar) with tubular water cooling and exits the spray nozzle at atmospheric pressure. Operating at atmospheric pressure minimizes the potential for high-pressure, high-volume water leaks into the furnace.

The spray-cooled technology relies upon the basic principles of heat transfer. Water droplet spray impingement is utilized to effectively and efficiently cool the hot face plate. The water exits the nozzles as a steady turbulent stream of tiny water droplets, each coming in contact and absorbing heat. The hot face plate is exposed to the heat source on one side and the water cooling sprays on the other. The hot face plate or 'skin' absorbs the heat and transfers it across its thickness. The water absorbs the heat from the skin, then is recycled.[1]

Water droplet impingement is more efficient and more optimal at cooling the surface area than the high velocity water stream flowing through a pipe, where only a portion of the water is in contact with the hot face. With spray cooling, every droplet of water is transported to the hot face and is effectively utilized for cooling. With a tubular system, the water velocity and volume are the drivers for heat removal. Spray cooling has been proven to be capable of removing high heat loads, in excess of 200,000 BTU/hr m^2 (600 KW/m^2).

Spray cooling is achieved by an arrangement of nozzles that produce a pattern of overlapping sprays. This creates a high degree of turbulence at atmospheric pressure which promotes the transfer of heat more efficiently than the conventional flood cooling methods at high pressure (Figures 2 and 3).[2]

Figure 2. Spray water droplet impingement on the hot face plate.

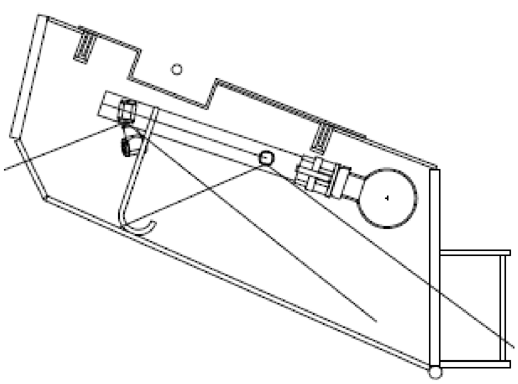

Figure 3. This schematic depicts a section view of the roof.

SPRAY COOLING DESIGN BASICS

The general configuration of equipment used in spray cooling is a double-walled design that includes a replaceable inner carbon steel hot face, an outer structural carbon steel dust cover, and an inner stainless steel and brass spray system in the annulus space that sprays water on the backside of the hot face.[3]

The hot face is comprised of carbon steel boiler plate, typically A516 Grade 70. Plate thicknesses can vary from 1/4 in. (6.3 mm) to 1/2 in. (12.7 mm) depending on the application. Spray cooling is a stress-free design that utilizes a single piece of boiler plate steel (hot face) which can freely expand and contract during operation. As the carbon steel plate can be easily repaired and rebuilt, expensive spares and long outages for replacing equipment can be eliminated.[4]

The dust cover, A36 plate, is the protective carbon steel covering that prevents dust and debris from entering the spray chamber. The spray chamber annulus is typically 16 to 20 in. (400 to 500 mm) wide. The dust cover has numerous access hatches to enable easy access for inspections and/or maintenance of the spray system.
The spray system is an arrangement of non-corrosive piping and spray nozzles which are removable using detachable spray bars that connect to a water supply header with cam locks. A single inlet feeds the header. The entire piping network is attached to the outer shell so that the hot face plate can be replaced without affecting the spray system. Cooling capacity can be readily changed by adjusting the amount of water distributed in a particular area of the equipment (Figure 4).[4]

Figure 4. Removable spray bars and overlapping water sprays are shown. (The dust cover is not shown.)

Cooling density across the hot face plate can be easily adjusted. The amount of cooling water within the equipment can be optimally utilized. This can be done by varying the size or quantity of nozzles in a specific area, or a combination of both. Patented, clog resistant nozzles, with varying flow rates ranging from 2.6 GPM up to 9.0 GPM can be oriented and positioned based on equipment hot spots and desired cooling requirements, see (Figure 5). Nozzles are threaded onto a stainless-steel spray bar and locked into position. Spray water can be directed towards hot spot areas and diverted from colder, less demanding areas. To increase water in a pressurized tubular circuit, water to the entire circuit needs to be increased.

The cooling water supply is maintained at a constant temperature and pressure. There is minimal to no temperature pick up or pressure drop across the supply header.

Figure 5. Clog resistant nozzles are available at variable flow rates.

The spent cooling water is collected at the bottom of the roof in the drain channel and evacuated. Discharged water can be drained by two methods, either via gravity, or evacuated with venturi pumps. With most stationary equipment, water can be rapidly removed via gravity. Tilting equipment, such as an EAF roof, requires evacuation with venturi pumps. Venturi pumps require only motive or drive water flow for their operation, and do not require any electrical motors or drives.

A common misconception is spray cooling utilizes evaporative cooling. Spray cooling is a non-evaporative cooling method. There is sufficient cooling water, so that evaporization does not occur. The water exits the spray nozzles at atmospheric pressure, cascades down the hot face plate, is collected in drains, and then returned into the water system. Fresh, new cool water flushes the water off the hot face. A typical water outlet temperature increase of 15°F to 20°F (8°C to 11°C) is typical.

Most of the hoses and piping are enclosed inside the spray-cooled part. The design of the roof or other equipment does not allow for air infiltration, which helps keep the heat inside the vessel, and keeps the dust and exhaust from escaping. This ensures many years of continual service with minimal maintenance.

Easy opening and safe access hatches allow quick and easy inspection of the hot face plate and spray system. Any required maintenance can be performed from outside the equipment without interrupting production.

ORIGINAL SPRAY-COOLED EAF ROOF DESIGN

The Ohio plant has (2) 20-ton AC Swindell Furnaces with 45 MVA transformers. Prior to spray cooling, the plant used a 12.5ft diameter refractory roof with a water-cooled steel ring (Figure 6). Typical brick or castable roofs cost roughly $15,000 per lining. This doesn't account for manpower to rebrick the roof. The refractory roofs were being replaced every week or less than that, totaling approximately $750,000 per year. This did not include downtime or maintenance for roof brick/castable falling out.

Figure 6. The original refractory roof.

The plant installed an oxy/gas CoJet™ burner in the sidewall in mid-2006. The additional chemical energy resulted in quicker melt in and heat times, but caused some premature damage to the refractory roof as well as the sidewall.

Under normal operating practices refractory roofs can typically achieve 250 to 500 heats before requiring replacement. This number can vary based on production levels, operations, and maintenance practices.

The main reasons for converting from refractory to spray cooling were refractory costs associated with reduced lifetime, easier maintenance, increased furnace availability, and safety.

A 12.5 ft diameter spray-cooled roof was designed to replace the refractory brick roof in 2008 (Figure 7). Based on geometry and heat loading, the new roof was designed with a cooling water flow of 525 GPM (120 m^3/hr.).

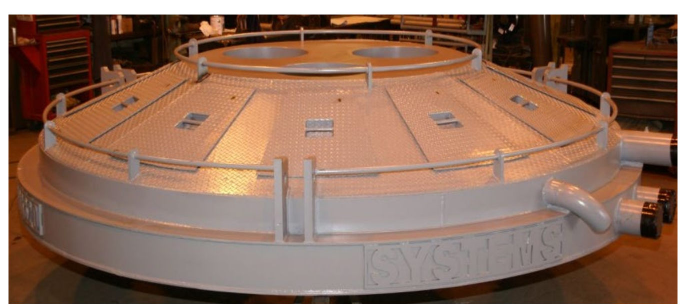

Figure 7. The original spray-cooled roof.

The roof water is supplied from the cooling tower. Manual basket strainers are located upstream of the roof inlet piping to filter out large particulate and debris.

The spray-cooled roof design incorporates (2) venturi pumps for water evacuation, one for the slag side and one for the tap side. Each venturi is capable of handling the total water requirements for the roof. The venturi pumps are driven by a motive water supply. Spent cooling water from the roof is drained and returned to a recirculation tank (Figure 8). Water from the tank is also used to power the venturi pumps. The tank water is then returned back to the cooling tower.

Figure 8. The recirculation tank, piping, and strainers.

The spray-cooled roof design incorporated (3) 24-inch (610 mm) electrode openings for each of the (3) electrode phases. The hot face was covered with 1 inch (25 mm) thick slag retainers to build and hold a slag accretion to help insulate and protect the steel hot face plate (Figure 9).

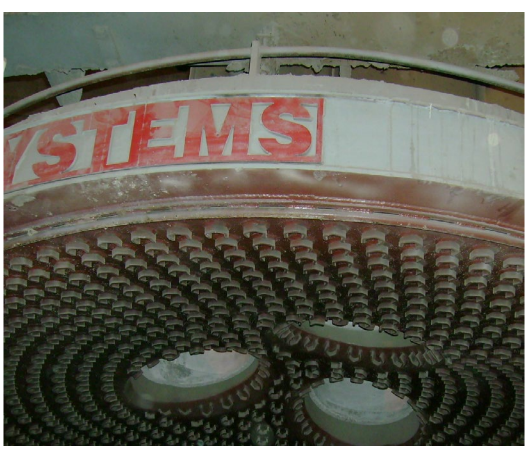

Figure 9. This photo shows the (3) electrode can openings and illustrates the slag retention system on the hot face.

The electrode openings were lined with (3) refractory cans or donuts to insulate and protect the steel roof from arc strikes and damage.

The original design ceramic sleeve liners for the electrode cans were vertical and supported from the top of the roof (Figure 10).

Figure 10. This photo shows the three refractory cans that insulate and protect the steel roof.

ORIGINAL SPRAY-COOLED EAF ROOF RESULTS AND LESSONS LEARNED

The spray-cooled roof was commissioned on EAF #2 in September 2008. The first heat was a success. After several heats the roof had a 1 inch to 2 inch (25mm to 50mm) thick coating of slag buildup.

The water supply temperature readings were 80°F (27°C) and the maximum water return temperatures were 95°F (35°C) resulting in a ΔT of 15°F (8°C) which was well within the design parameters. Motive water pressure was recorded at 25 psi (1.7 bar), a little lower than design.

After 1 month, the vertical refractory cans started to crack and break, and the roof succumbed to arc strikes where the refractory cans had been located (Figure 11).

Figure 11. This photo shows the damaged refractory cans.

In early 2009, the straight electrode cans were replaced with tapered electrode cans in order to prevent the ceramic can inserts from cracking and falling into the furnace. The roof was modified to accept the new tapered refractory cans.

The tapered electrode cans worked well and reduced the cracking and arcing issue. However, as the off-gas draft is evacuated through the electrode ports, the new tapered designed resulted in slag build up along the tapered refractory section (Figure 12). The slag deposits resulted in damage to the electrodes and reduced draft.

Figure 12. The photo above shows slag build up in the tapered electrode can.

In May 2011, as part of general maintenance, the roof hot face was removed and replaced with a new hot face plate and slag retainers. The roof had over 2.5 years of service life.

In mid-2013, a roof modification was made to convert from a 3-piece delta (3 single cans) to a 1-piece refractory delta (Figure 13). The electrode openings were vertical to minimize any slag accretion. The 1-piece design reduced the issues of refractory can damage and arcing. The new design also allowed for better cooling around the circumference of the delta ring verses trying to cool in-between each electrode can.

Figure 13. The new roof with new a 1-piece refractory delta replacement for the previous 3-piece delta.

In 2019, the spray-cooled roof was removed from service due to arcing issues and significant damage (Figure 14). The roof had not been properly maintained or repaired since 2013 and was deemed not repairable and subsequently scrapped.

Figure 14. The photo above shows the returned spray-cooled damaged roof.

The roof was designed to use 6-inch hoses for the supply and return water lines. As seen in Figure 14, the 6-inch pipe spools were reduced down to 4-inch hoses. This change resulted in less cooling water to the roof. It also resulted in difficulties draining water from the roof, as the 6-inch venturi pumps had issues draining water through the 4-inch hoses. The roof was only able to achieve ~70% of the design flow.

NEW 'IMPROVED' SPRAY-COOLED ROOF DESIGN

A new spray-cooled roof was delivered in November 2021 and is still in service today. As of November 2023, the roof has been in service for approximately 6,000 heats.

The new spray-cooled roof design was modified to incorporate several upgrades:

1. The roof again incorporated the 1-piece delta design.
2. An upgraded spray system with additional water coverage above and across from the Praxair CoJet burner was implemented.
3. The access hatches were redesigned to allow for easier removal and a tighter fit to prevent them from detaching during furnace tilting.

To properly accommodate the 525 GPM (120 m^3/hr) design flow rate, the 4-inch water supply and return hoses were replaced with new 6-inch hoses. The design flow rate of 525 GPM was achieved as was the proper motive water flow rate.

In March of 2022, an inclinometer and a "bypass" valve were installed on the water piping to reduce the water supply while the furnace was tapping. This was done to eliminate any chance of water leaking during tapping. The valve is opened when the furnace tilt switch hits 15 degrees. The water flow is reduced to 350 GPM for the balance of the tapping sequence.

OPERATIONAL DATA

- The 1-piece refractory delta costs $8,000 to $9,000 each.
- The delta is changed every 2 weeks or 12 operating days.
- The mill reports that is takes 30 minutes to change the refractory delta.
- In May 2022, the plant arced a hole in the roof during the night shift. Maintenance was able to quickly weld repair the carbon steel hot face plate, with minimal downtime.
- The original refractory roof was changed approximately every 7 to 8 days at a cost of roughly $15,000 in today's market.
- The original spray-cooled roof repair cycle was once every 2 to 2.5 year (5,000 to 6,000 heats)
- After the 1-piece delta was implemented, roof damage due to arcing was significantly reduced.
- The "new" roof has been in service with very minimal maintenance for over 2 years.
- The spray-cooled roof weighs ~10,000 lbs. and is substantially lighter than the refractory roof saving on lift cylinders.
- The plant is looking at a new spray-cooled roof for their #1 EAF.
- The plant is also investigating the addition of a spray-cooled upper shell.

The lifetime of a refractory roof is a few weeks. After this time, the roof is removed and rebricked. The lifetime of a spray-cooled piece of equipment is indefinite, with several customers having equipment lasting 10 to 15+ years. A significant advantage of spray cooled versus refractory is the service life and the ability to rebuild the equipment. Rebuilding or 'reskinning' can be done repeatedly and is as simple as replacing a piece of carbon steel plate. Foundries can save 60% to 70% by rebuilding equipment instead of replacing it. The increase in the number of heats or operating time, plus the elimination of rebricking costs, make for a quick ROI with spray-cooled equipment.

WATER LEAKS AND SAFETY

When operating water-cooled equipment in a metalcasting facility, damage is inevitable. When a crack or hole does develop, the amount of leaking water into the furnace per second is critical. With a pressurized cooling circuit, equipment operates in the range of 60 to 75 psi (4 bar to 5 bar). With spray cooling, the water supply pressure to the equipment is approximately 35 psi (2.4 bar). The water leaves the spray nozzles at atmospheric pressure. In the event of a leak or crack, the amount of discharged water is minimal.

For example, a two square-inch hole in a tubular panel operating at 60 psi (4 bar) will force approximately 16,000 gallons per hour (~60,000 liters per hour) into the furnace. By comparison, the same two square-inch hole in the spray cooling practice will introduce less than five gallons into the furnace in the same hour.[4] By minimizing the amount of water into the furnace, in this case over 3,000 times more, the risks of a water or steam explosion are reduced (Figure 13).

Figure 15. The above pictures show a typical leak in a spray-cooling roof (left) compared to a pressurized tubular system (right), 5 GPH vs. 16,000 GPH.

CONCLUSIONS

Prior to the invention of the spray-cooled technology, equipment that was subjected to hot environments was protected by either refractory linings or by pressurized water-cooling circuits. Refractory linings have a relatively short useful life compared to water cooling, and pressurized water systems can pose a very serious safety risk.

The plant has numerous years of operating experience on their EAF's with refractory roofs, and over 10 years experience with spray-cooled roofs (both the old and new designs). They have firsthand experience with the pros and cons of each system. The knowledge developed over the years highlights the primary advantages and justifications of spray cooling. The non-pressurized safety feature, combined with the ease of maintenance and lower maintenance costs (rebuild-ability of the hot face versus rebricking the roof), makes spray cooling cost-effective for foundry applications.

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