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Comparison of an Impedance Heating System to Mineral Insulated Heat Trace for Power Tower Applications

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ABSTRACT

A non-conventional type of heating system is being tested at Sandia National Laboratories for solar thermal power tower applications. In this system, called impedance heating, electric current flows directly through the pipe to maintain the desired temperature. The pipe becomes the resistor where the heat is generated. Impedance heating has many advantages over previously used mineral insulated (MI) heat trace. An impedance heating system should be much more reliable than heat trace cable since delicate junctions and cabling are not used and the main component, a transformer, is inherently reliable. A big advantage of impedance heating is the system can be sized to rapidly heat up the piping to provide rapid response times necessary in cyclic power plants such as solar power towers. In this paper, experimental results from testing an impedance heating system are compared to MI heat trace. We found impedance heating was able to heat piping rapidly and effectively. There were not significant stray currents and impedance heating did not affect instrumentation.

BACKGROUND

In a solar, molten-salt central-receiver power plant, heliostats focus sunlight on to a receiver mounted on top of a centrally located tower. The heat transfer fluid, molten nitrate salt (60% sodium nitrate, 40% potassium nitrate), is pumped from a "cold" storage tank and heated by the illuminated receiver from 290°C to 565°C. The hot salt is stored in a "hot" tank where it can be used to produce steam to power a Rankine turbine and generate electricity (Chavez, *et al, 1995*). The key advantage of molten salt is its useful operating temperature range is well matched to the Rankine thermodynamic cycle.

Unfortunately, nitrate salt has a high freezing point (approximately 220°C) (Cook, McMordie, 1989), so all the salt piping must be heated. Mineral insulated (MI) heat tracing has been used extensively in molten salt applications to maintain the temperature of piping and components above the salt freezing point, typically at 290°C. If mineral insulated heat trace is not installed correctly it can be unreliable, cause non-uniform heating, especially in large pipes, or cause difficulties with controlling pipe temperature. In addition, the amount of power applied to the pipe by heat trace is limited by its watt density and physical constraints of attaching the cables to the pipe. This makes the thermal response of the system relatively slow - limiting the rate at which the plant can be brought into operation and reducing overall plant efficiency.

Most problems with heat trace in this application can be traced to a lack of quality control in the design and installation. An example of the consequences of improperly installed heat trace is the initial installation of heat trace in the Solar Two 10 MWe power plant. In some heat trace circuits, the heat trace cable was made too long for the pipe length and valves in that circuit. The installers doubled back the heat trace in portions of the pipe which caused localized overheating and spallation of metal from the pipe. These pieces of metal became entrained in the salt and were trapped in the receiver. Some pieces actually blocked flow to receiver tubes causing them to overheat and warp.

Impedance heating generates heat directly in a pipeline by flowing electrical current through the pipeline or vessel wall by direct connection to a low voltage, high current source from a dual-winding transformer. This type of heating uniformly heats the pipe circumferentially. It has been used in several petrochemical applications at very high temperatures. An impedance heating system can be designed to heat up the piping rapidly so the system can respond quickly. It could be simpler to install and should be much more reliable. It is best suited for long straight runs of pipe without components.

OBJECTIVE OF THE TEST

Manufacturers of impedance heating systems claim thousands of highly reliable systems have been installed in the past thirty years. Despite this track record, there are concerns whether this type of heating system is complementary with high temperature solar thermal

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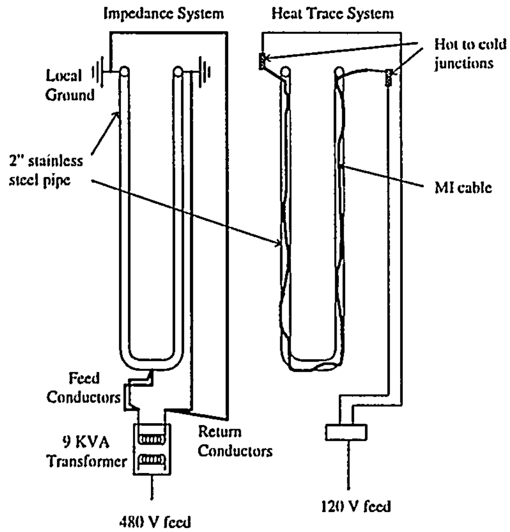

Figure 1. Schematic of impedance heating and MI heat trace system.

applications where there is deep temperature cycling, thermal shock, and molten salt containment problems. Also, since high currents are flowing through the pipe, there is a safety concern for site personnel who may come in contact with electrically energized piping. Another concern is the effect of these currents on instrumentation and components. The following objectives have been set to address these issues and evaluate the relative merit of MI heat trace versus impedance heating systems for molten-salt, central-receiver applications:

1. Verify the safety of an impedance system - the presence of stray currents in the branch loop, pipe supports, and on instrumentation shields as well as the voltage of the energized pipe itself.
2. Determine the affects of an impedance system on thermocouples, transducers, and other forms of instrumentation.
3. Quantify the relative power consumption (kWhr) of impedance heating compared to MI heat trace.
4. Determine the rate at which each system will bring dry piping to temperature.
5. Determine the rate at which each system will unthaw a pipe filled with frozen salt.
6. Determine if an impedance heating system will provide a longer life of the pipe after repeated freeze/thaw cycles compared to heat trace.
7. Evaluate the relative ease of repair and modification of the two systems - subjective evaluation after using.
8. Determine if MI heat trace can safely be used as supplemental heating at in impedance circuits.
9. Perform a subjective evaluation of the relative maintenance requirements for each system.

DESCRIPTION OF THE HARDWARE SYSTEM

The impedance heating system was purchased from Industrial Engineering and Equipment Company (INDEECO) for this test. The system employs a 9 KVA transformer with a secondary voltage set to 5.8 volts that put out a current of approximately 932 amps. The electrical connectors to the pipe have been designed for the amperage requirements of the test section, but small enough so that they are not a heat sink to the pipe.

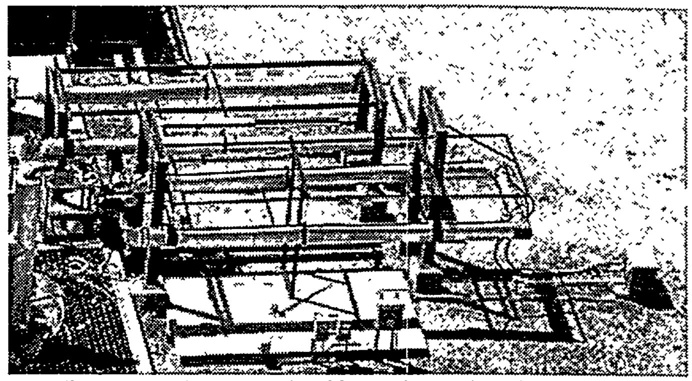

Figure 2. Photograph of impedance heating system (foreground) and heat trace system (background).

The impedance system was installed on a 15.8 m (52 feet) section of 5.1 cm (2.0 inch - nominal) schedule 40 stainless steel pipe. The current can be fed through a pipe in one of three ways: 1) a midpoint feed where the current flows from the electrical mid point of the pipe with the return paths at each end of the pipe, 2) an end feed connection where current is fed from the beginning of the section desired to be heated and the current returns at the other end of the pipe, and 3) a dual-line feed connection which is similar to an end feed connection but applied to parallel pipes. The parallel pipes are jumpered together at the electrical midpoint. The current feeds from the end of one pipe, through the electrical midpoint to the parallel pipe and returns to the transformer.

For this system, we chose a midpoint feed because the pipe can be electrically isolated from the rest of the piping. This is also the most likely configuration to be used in a molten-salt central-receiver system. The end-feed connection requires non-conducting flanges to electrically isolate the pipe, which could add complications to the piping design and may not be compatible with molten salt.

The heat trace system consisted of 16.5 m (54 feet) of single-element mineral-insulated heat trace with a total power rating of 2680 W that operated on 120 VAC. It was installed on a similar 15.8 m (52 feet) section of 5.1 cm (2.0 inch - nominal) schedule 40 stainless steel pipe. The heat trace cable was attached to the pipe with band wires parallel to its axis in a slightly serpentine fashion. It was covered with metal foil to provide a protective cover and to distribute the heat over a larger area of the pipe. At the ends of the heat trace cable were hot-to-cold junctions to transition from the heat element to the conductor wire.

Both pipes were insulated identically. Two and one-half centimeter thick of soft Koawool insulation was installed over each pipe. This was covered with ten centimeter of fiberglass insulation made from three layers: a 3.8 cm layer covered with a 3.8 cm layer, covered with a 2.5 cm layer. The insulation joints were lapped to prevent air infiltration as the pipe heated up and expanded. The insulation was then covered with aluminum lagging and the seams sealed.

A schematic of the setup is shown in Figure 1. Figure 2 shows the system in place at the National Solar Thermal Test Facility at Sandia National Labs in Albuquerque, NM. Each system had three sheathed, ungrounded type K thermocouples. We installed additional instrumentation in the impedance heating system to determine any

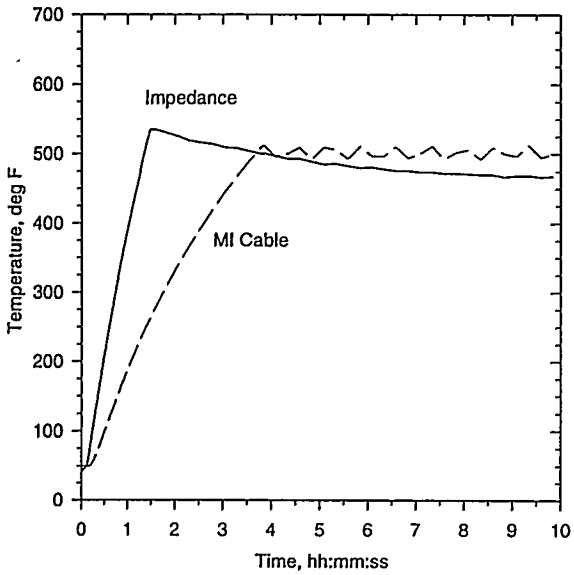

Figure 3. Temperature responses of the impedance and MI heat trace pipe loops during heat up with pipes empty.

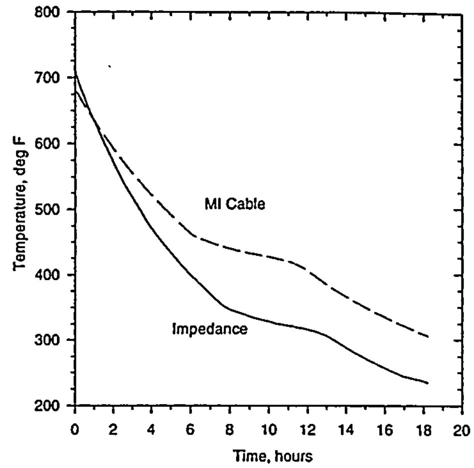

Figure 4. Measured cool down of each heating system with pipes filled with salt.

effects of stray currents. These instruments included: resistive temperature detectors (RTDs), a pressure transducer and a valve positioner.

STRAY CURRENTS AND VOLTAGES TEST

This test applied only to the impedance pipe system and was designed to measure the level of stray currents and voltages in the piping beyond the grounded elbows and in the surrounding support structures (caused by induction). In addition, we measured stray current in the instrumentation wire shielding.

In this test, we activated the impedance heating system and brought the temperature of the pipe to 52°C (125°F). We measured the currents between the grounded elbows at both ends of the pipe loop using an amp-probe. The measured current from the north end of the pipe to the south was 6.9 amps. There was no current to ground. These stray currents are not a hazard since the voltage was very low, 5.3 mV, and are due to an imbalance in current between the two flow paths.

We measured and recorded the return current to the transformer secondary from each end of the pipe loop. In the north return leg, the current was measured to be 471 amps and in the south leg, 461 amps. Ideally, the currents in both legs would be equal.

No measurable stray currents were found in the piping support assembly that may have been induced from the larger currents in the impedance-heated piping. Next we measured stray currents on the instrumentation wire shieldings. It is critical that instruments installed in an impedance system are not grounded. We found no measurable current in the wire shieldings of any of the instruments. The instruments were not affected by the current flowing through the pipe.

EMPTY PIPE HEAT UP TEST

In this test, we measured the rate and power consumption of each heater necessary to heat the empty pipe from ambient temperature (10°C) to 260°C. We also measured their power consumption required to maintain its temperature at 260°C for 48 hours. Figure 3 shows the temperature response while heating each pipe (empty). The results of these measurements are shown in Table 1. As can be seen, the impedance system heated the pipe to 260°C in about 1/3 the time it took the MI heat trace system. The impedance system, though, consumed about 20% more energy. The average power consumed by the impedance system to maintain the pipe at the set point was 65% more than MI heat trace system.

Table 1. Summary of measurements from dry heat up test.

System	Time to Reach 260°C from 10°C, hrs:min	Energy Usage to Reach 260°C, kWhr	Average Power to Maintain 260°C, W
Impedance	1:25	7.65	1400
MI Heat Trace	3:50	6.41	870

FILLED PIPE TEST

Both pipes were filled with nitrate salt to a level approximately half full to determine if there were any non-uniform temperature distributions along the length of the pipe. This is a concern with the impedance system that heat electrically conducting fluids because the resistance in the pipe will change where there is the fluid. There were no problems with heating a pipe half full of salt since salt in not very electrically conductive.

Next we completely filled both pipes with salt and measured their steady state power consumption to maintain 260°C. To determine if the difference in power consumption between the two systems was due to inefficiencies in the impedance system or due to thermal loss, we heated both systems to approximately 370°C and let them cool. See Figure 4. By measuring the rate of change of temperature at 260°C, we estimated the thermal heat loss of the pipe accounting for the mass of the pipe and salt from Equation (1).

$$Q = (M_{pipe}Cp_{pipe} + M_{salt}Cp_{salt})\frac{dT}{dt} \qquad \text{Eq. (1)}$$

Table 2. Measured power consumption and heat loss for pipes full of salt.

System	Measured power to maintain 260°C, W	Measured heat loss at 260°C, W
Impedance	1530	1250
MI Heat Trace	850	790

The rate of temperature change was based on one of three thermocouples in each circuit. All the thermocouples in a particular system had the same rate. Table 2 summarizes the results. As can be seen, the impedance system had much higher *thermal* losses. This is significant because both sets of pipes were thought to be insulated the same. The impedance heating system, though, has large electrical connectors at the mid point and the ends of the pipe, which act as fins. We initially believed these significantly added to the heat loss. We measured the power consumption of the impedance system before and after insulating the conductors. We found that there was insignificant difference in the power consumption.

BOTH SYSTEMS ON SAME PIPE

Since the heat loss from the pipe that had the impedance heating system was so much higher than the pipe that had the heat trace system, the power consumption of each heating system needed to be validated on the *same* pipe. To do this, we removed the impedance heating system from its pipe and installed it on the pipe that had the MI heat trace system. We also insulated the electrical connectors of the impedance heating system.

We heated the pipe (which was full of salt) from ambient with each system and measured the heatup rate and power consumption and then measured the thermal loss after the pipe had been heat with each system.

The response of the pipe (filled with salt) heated by each system is shown in Figure 5. Note there are discontinuities in the slopes of the lines between 204°C and 260°C (400 and 500°F). This occurs when the salt has a phase transformation (solid to liquid). Table 3 summarizes results from these tests. The heat trace system took over 14 hours to heat the pipe, melt the salt, and bring them to 290°C (550°F). The impedance heating system took less than 4 hours. The electrical energy used by the heat trace system to heat up the pipe, melt and heat the salt was 23% more than the impedance system. This is primarily due to the fact that it took longer with heat trace to heat the pipe and melt the salt so more energy was lost to the environment.

Figure 6 shows the temperature profiles as the pipe cools after being heated by each system. Note that the profiles and slopes are nearly identical between 304°C and 232°C (580°F and 450°F). This shows that the thermal losses are nearly identical, as they should be, since this is the same pipe, only heated with different systems. Table 4 summarizes electrical power measurements averaged over various time intervals and the measured heat loss to maintain the pipe at 290°C (550°F) based on Equation (1).

We believe that the differences in thermal losses measured in the previous tests where each system was installed on a separate pipe was solely due to differences insulation. Slight differences in installation techniques could result in large differences.

REPEATED FREEZING AND THAWING TEST

Another test involved freezing and thawing salt in pipes that were full of molten salt. It attempted to determine differences in the way the two systems handles freezing and thawing of molten salt in a pipe. Since the impedance heating system uniformly heats the pipe in the circumferential direction, frozen salt could melt from the edges inward and may allow the salt to slide as it thaws. Thawing molten salt in pipes can be very damaging since nitrate salt expands upon melting (Pacheco and Dunkin, 1996). We conducted this test when the heating system were installed on separate pipes. We cycled the temperature of the pipes between approximately 25°C and 260°C for 15 cycles. Neither pipe ruptured and there was little difference between the thawing methods.

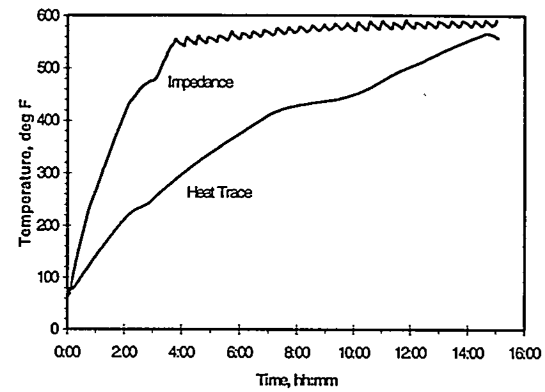

Figure 5. Temperature response of the same pipe filled with salt heated by heat trace and heated with impedance heating system.

Table 3. Summary of results from heat up test with pipe filled with salt. Both systems on single pipe

System	Time to heat pipe from ambient to 290°C (550°F), hh:mm	Electrical energy to heat pipe, kWhr
Heat Trace	14:40	24.98
Impedance	3:47	20.32

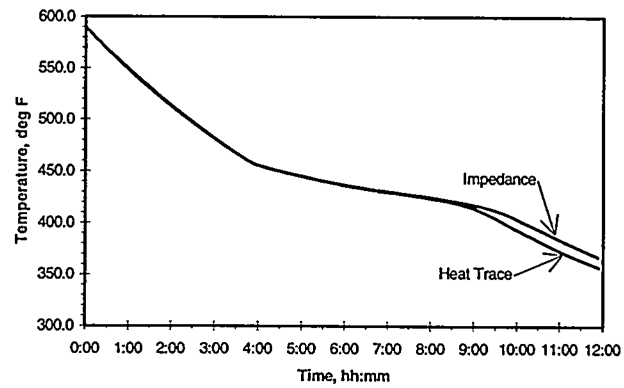

Figure 6. Pipe cool down test after pipe was heated by each system. The pipe was full of salt.

Table 4. Summary of average power measurements over various intervals and heat loss measurements for each system with pipe filled with salt.

Heat Trace System		
Date	Average Power to Maintain 290° (550°F), We	Days Averaged Over
5/24/96	1195	1
8/9/96	1080	1
8/13/96	1057	1
8/14/96	1070	1
8/21/96	1023	1
8/22/96	1060	1
8/23/96	1026	1
8/26/96	1048	3
8/27/96	1051	1
Average	**1064**	**11**
Measured Heat Loss at 290°C (550°F): 909 W_{th}		
Impedance Heating System		
Date	Average Power to Maintain 290° (550°F), W_e	Days Averaged Over
5/30/96	1333	1
6/20/96	1204	1
6/21/96	1186	1
8/1/96	1210	1
8/2/96	1206	1
8/5/96	1218	3
8/6/96	1197	1
Average	**1221**	**9**
Measured Heat Loss at 290°C (550°F): 910 W_{th}		

CONCLUSIONS

The impedance heating system is a safe, easy-to-install alternative to MI heat trace. It is best suited for long runs of piping without components (e.g., valves) so it can easily be installed and balanced. There are not significant stray currents induced in the support structure that could be hazardous to personnel. It can be sized to rapidly heat up a section of pipe to respond to changes in the state of plant. We found that the steady-state power consumption at 290°C (550°F) to be approximately 15% higher in the impedance heating than in the heat trace system. This was primarily due to higher electrical losses in the feed cables and transformer. Using large feed cables to reduce these losses might not be practical since the cables used in these tests were already quite large.

ACKNOWLEDGEMENTS

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