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Factors, Influencing Radiant Tube Life

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Abstract:

A good durability of radiant tubes is essential for a profitable operation of a strip line. There are several factors influencing the radiant tube life:

- tube design
    - tube material
    - structural design
    - workmanship
- operation
    - production rate
    - burner control and design
    - furnace control
- maintenance

The presentation will cover different tube designs fired with recuperative and regenerative burners. The awareness of these interrelationships should help to improve tube life in existing and new strip lines.

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Introduction

Tube life is essential for every operation of a strip line. Besides the replacement or repair cost for the tube, reduced tonnage or the need for a line stop ahead of schedule are unwanted effects of a short tube life. The reasons for tube damage can be manifold and often its not just one single cause but a combination of several influencing parameters. It is important to analyze tube failures properly as a joint effort between suppliers and users. Only that enables to improve tube life by design changes, changing operating conditions or other measures.

Tube Design

Vertical strip lines are predominately fitted with either W-tubes or Double-P-Tubes. The reason is their relatively large radiating surface area per unit which keeps the number of burners and radiant tubes at an acceptable level at large furnaces. In horizontal strip lines often U-tubes or Single-Ended-Tubes are used.

Tube Material

Radiant tubes are made from cast tubes and bends or are fabricated from sheet metal. Single-Ended-Tubes and U-Tubes are additionally available as SiSiC-tubes (silicon infiltraded silicon carbide).
It has to be considered that metal radiant tubes in galvanizing lines are operated at their upper temperature limits. There are several mechanisms like hot corrosion and metal dusting which can cause failures, but in galvanizing its usually the creep strength which is the determining property. At temperatures above 1700°F the creep strength is dropping fast. Creeping occurs faster at higher temperatures. Figures 1 shows a simple creeping test for metal strips (brand names deleted) which were exposed to high temperature causing creeping from bending stress of their own weight. The dependency of creep stress, time and temperature is often described by the Larson-Miller /1/ parameter. So there is no strict temperature limit for a tube operation, but the higher the tube temperature the shorter the time is, which leads to tube deformation.

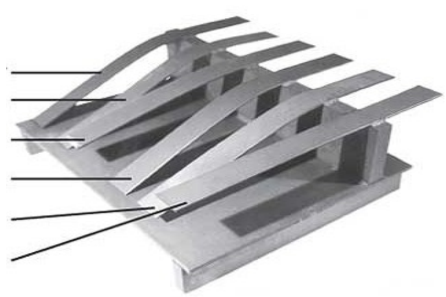

Figure 1: creeping (100hrs at 2000°F), source: Haynes

Radiant tube material has high nickel contents to improve thermal properties but nickel also makes the tube material quite expensive. Regarding sagging, it does not matter if cast or fabricated tubes are used because the higher structural strength of the cast tubes is offset by the higher weight. There is no clear indication for a statement that either cast or fabricated tubes provide a better length of life.

Ceramic material has superior thermal property and its strength is comparable to steel at room temperature even at temperatures up to 2300°F. That enables the installation of Single-Ended-Tubes in horizontal lines to be installed cantilever without any support. On the other side, ceramic tubes are brittle and not forgiving in regard to handling errors or strip breakage which can cause major damage. This is also a reason why ceramic tubes are not installed in vertical lines where the falling strip in case of a strip breakage could destroy a large number of ceramic radiant tubes. Ceramic material also has a good chemical resistance to many substances but alkali (sodium, potassium) originating from strip cleaning agents or other sources attacks the ceramic material. Another known source of trouble is extremely dry hydrogen, which can destroy the SiSiC protection layer at very high temperatures. The hydrogen/nitrogen atmosphere of galvanizing lines is not critical in that regard.

Structural Design

Since the material properties are usually close to their limits, the structural design of a radiant tube is critical. The structural design has to provide sufficient stability against bending and sagging. On the other hand, the tube must be able to freely expand. A typical radiant tube expands one to two inches in length from room to operating temperature. There must be enough space to expand but it also must be ensured, that the end of the tube is not slipping off the support when the radiant tube contracts. In this regard a proper radiant tube design can use principles from bridge design with pinned and a roller support (Figure 2). Structures which prevent the tube from free expansion can do more harm than good.

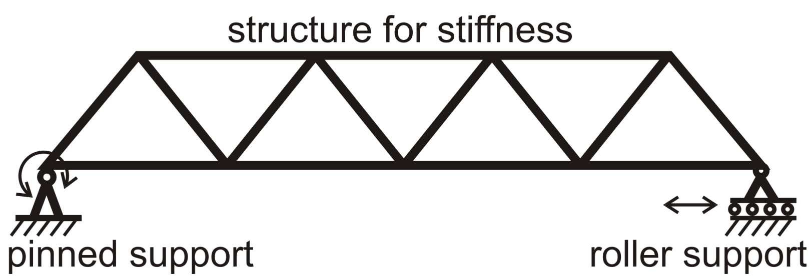

Figure 2: structural design

Single-Ended-Tubes with larger diameters are stronger since their weight increases only by the power of two with the diameter while the section modulus is increasing by the power of three and the area moment of inertia is increasing by the power of four.

Double-P-Tubes are very strong if installed vertically, comparable to an I-beam. But it must be insured that the surface temperatures are homogenous to avoid internal stresses from different elongation of the tube legs.

U- and W-Tube temperatures are not as uniform and therefore require at least one loose end tube which is sealed against the furnace atmosphere using a compensator outside of the furnace. W-Tubes often have several supports and joints and sliders which are increasing the strength while allowing tube expansion and contraction.

The tube deformation over time will eventually lead to complete damage because the tube cannot expand properly anymore or it slips out of the support. Besides the sagging of the tubes, collapsing caused by the internal negative tube pressure has to be considered. Therefore unnecessary high negative pressure has to be avoided.

Another important design feature is to provide optimized flow conditions in the tube. Recirculation is essential for P- and Double-P-Tubes. Also, a very narrow radius on U- and W-tubes can lead to a detached flow (stall) with negative effects.

Computer methods like FEM (finite-element-method) were used to investigate radiant tube design but up to now these were rather academic exercises since boundary conditions are difficult to define and high temperature creeping is difficult to model. There were also efforts to measure tube stresses using high temperature strain gauges which only gave questionable results.

So improving structural tube designs is a lengthy process since it usually takes several years until a result becomes visible.

Workmanship

Welding of alloy materials requires a lot of experience and only specially trained and capable welders are able to provide good results. Some of the welds can be automated but some need to be welded manually. If done properly, welding seams do not represent a cause for tube failures. It must be judged how much money should be spent on welding seam inspection which can be very costly. It is recommended to determine a percentage of welding seams which are tested using x-ray or dye penetrant test and choose more inexpensive methods for the remaining welds.

Fabricated tubes use either welded or stamped bends. Stamped bends provide a smoother flow inside the tubes and less stress by avoiding sharp corners. However, the stamping must be carried out in a way that results in an even material thickness. Stamping molds are quite expensive and can only be justified for standardized tube dimensions.

The burner flanges must stay flat and be orthogonal related to the tube to ensure proper sealing and burner positioning.

Operation

Production Rate

Every furnace is designed for a certain production rate. The theoretical limit can be calculated using the so called "lumped capacitance method" /2/. This formula is applicable if the Biot- and Sparrow-number are small, meaning that the heat transfer inside the strip is much faster than the heat transfer at the strip surface, which is true in strip lines. The formula is usually presented to calculate heating time but can easily be transformed to calculate production of steel in a steady operated galvanizing line.

$$Pr := \frac{4 \quad 2\,b\,l \quad T_f^{3}}{c_p \left[\ln\left[\frac{(T_f + T_2)\,(T_f - T_1)}{(T_f - T_2)\,(T_f + T_1)} \right] + 2\,\mathrm{atan}\left[\frac{T_f\,(T_2 - T_1)}{T_f^{2} + T_2\,T_1} \right] \right]}$$

Pr production [kg/s]
radiation exchange factor
B strip width [m]
l heated strip length [m]
Stefan Bolzmann constant $:= 5.67\,10^{-8}\,\frac{\mathrm{watt}}{m^2\,K^4}$
T_f ideal furnace temperature
c_p specific heat capacity [joule/kg K]
T_1 strip entry temperature [°C]
T_2 strip final temperature [°C]

Of course, the theoretical number will never be achieved in a real furnace. Besides its weaknesses and simplifications, the lumped capacitance method is valuable for quick analysis and a comparison of different furnaces and production scenarios.

A more detailed calculation of the production rate is based on experience and more sophisticated models which include nonlinear thermal properties and numerous other factors.

It is obvious, that exceeding the design production rates will compromise equipment life, especially radiant tube life.

Burner control and Design

The burner should provide the energy to the heating zone according to the heat demand determined by the furnace control. There are two control methods:

- proportional control and
- pulse firing or on/off control

Proportional controlled systems can be found on U-Tubes and W-Tubes whereas Double-P-Tubes are exclusively fired on/off.

In pulse fired systems, it is important to choose the correct burner cycle times. The cycle times should not be too short but the more common incident is that cycle times are too long, causing the radiant tube to heat up and cool down too far. Typical cycle times should be in a range of one to two minutes, depending on the heat output. This results in temperature variations of less than 30°F not causing any stress on the radiant tube structure.

For proportional controlled systems, it is important not to exceed the turn-down ratio which is specified to avoid hot spots on the tube. Since the flow conditions are interconnected for zone controlled systems, burners need to be re-tuned if single burners are out of service.

In U- and W-Tubes, the flame length is critical for avoiding hot spots. If the flame is too long, there will be a hot spot at the first bend. If the flame is to short, there will be a hot spot near the burner tip. These hot spot have the potential to damage the radiant tube in a short time. Besides the burner design, flame length depends also on the burner turn down, the fuel gas composition, distorted burner tips, air preheat and air fuel ratio.

Vertical galvanizing lines are operated with a negative tube pressure to prevent combustion products from leaking into the furnace. This can be achieved by providing a negative exhaust pressure. Some systems, call pull-systems use that negative pressure to suck the ambient combustion air into the radiant tube. However it is difficult to maintain proper flow to all burners. That's why modern systems are operated as push-pull systems where the flow could be better controlled on the cold side.

On some installations, it was found that radiant tube safety temperature switches were misused to control the burner which resulted in the recording of thousands of safety shut offs. That's seriously harming tube life but also reducing production capability since the tubes remain off for a certain time until the radiant tube temperature falls below a certain level. This creates a thermal cycling at a high temperature level, causing maximum stress on the tubes.

Furnace control

Most furnace models rely on temperature measurements in the furnace or at the tube to determine a furnace temperature using thermocouples and measure the strip temperature using pyrometers. Both measurements have their specifics. With a thermocouple it depends on where you place it. You can measure pretty much any temperature between the colder strip or the hotter radiant tube surface. That has to be considered when applying the furnace model.

Pyrometers are used to measure the strip temperature. If they are used to measure the final strip temperature, their readings can be calibrated by analyzing the strip properties. When used between a direct and a radiant tube heated furnace section, minimal deviation of the strip emissivity can result in false temperature readings which completely shift the heat burden from the direct fired section to the radiant tube furnace or vice versa..

Also readings from the tube surface temperature can easily vary by several tens degrees what can be critical if the radiant tube is operated at the upper temperature limit. The accuracy depends on the contact between the thermocouple and the radiant tube as well as the position of the thermocouple.

For this reason, its a good thing to not only rely on temperature readings (and even more temperature readings) but also to compare the numbers with the heat balance of the furnace and to check all numbers for plausibility. The heat input in a zone in combination with strip data, especially the strip width, can give very valuable information. For example: a high heat input in a location where a narrow strip is already quite hot means a lot of stress for the radiant tubes.

Radiant tubes prefer a smooth operation. Furnace controls behave quite different. In some cases, heat demand goes wildly up and down, others change these parameters moderately with abrupt changes only if a change in strip parameters makes it necessary. Avoiding these constant and unnecessary temperature fluctuations of several hundred degrees can improve tube life considerably.

Again, analyzing the heat flux in the furnace is an important task to optimize production and equipment life. Ideally the heat flux distribution is smooth and is decreasing when the strip gets hotter as it is traveling through the furnace.

Maintenance

Proper maintenance is important for many reasons and usually pays for itself by better fuel economy, better product quality, higher productivity and less replacement parts. Regarding tube life, maintenance is important to detect situations early which could result in radiant tube damage. This could be:

- out of tune burners
- broken gaskets
- soot buildups
- clogged orifices
- covered tubes
- heat damaged burners
- or other

Summary

A radiant tube is a costly part, mainly because high nickel alloy or ceramic materials are expensive. A proper tube design and workmanship is a prerequisite for a good tube life.

But also tube operation plays an important role. Very high and strongly fluctuating temperatures should be avoided. Controlling the heat input using the temperature safety shut off limits guarantees poor tube life.

It is helpful to check the heat input profile which should show lower heat fluxes as the strip temperature gets higher and should not fluctuate too much.

Cooperation of burner supplier, tube supplier, furnace supplier and customer is essential.

References

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