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Research Article

# Investigation of Premature Failure of Brass Tubes Leaking in a Heat Exchanger

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## Abstract

Failure investigation of a typical heat exchanger was conducted. The equipment comprised brass tubes (C23000) fitted with an AISI 1020 "turbulator spring" at its center. The heat exchanger developed water leaks during service. Ideally, the heat exchanger has a recommended life of 40,000 hours, but the one in question only lasted 12,000 hours. Treated water at an operating pressure of 64 psi. was circulated through the brass tubes with inlet and outlet temperatures of 47 °C and 57 °C, respectively. On the external surfaces of the tubes, an air/fuel mixture entered the heat exchanger, at a temperature of 75 °C, and left at 52 °C. As such, the heat exchanger was designed to lower the air/fuel mixture's temperature by 20 °C, before the gaseous mixture entered an engine, for optimum combustion conditions. Scanning Electron Microscope (SEM) and Energy Dispersive Spectroscopic (EDS) analysis revealed that the surface areas of tubes suffering from corrosion, being depleted in zinc versus the bulk zinc content of the alloy; an indication of dezincification. Macroscopic examination of one of the sectioned tubes showed a small pinhole at the surface, approximately 12 mm, from the end of the tube. It exhibited slight bulging, characteristic of thermomechanical damage. The inside adjacent areas showed excessive pitting. Evidence of erosion-corrosion as a result of the combined effect of galvanic induced corrosion, due to material mismatch of the tube and the turbulator spring, coupled with an erosion of the brass tube, by the continuous vibration of the turbulator spring in contact with it, was also observed.

## Introduction

Heat exchanger failures are typically complex and generally attributed to either mechanical failures, chemically induced corrosion, or to a combination of both. Mechanical failures result due to thermal fatigue, thermal expansion, or to metal erosion, in which fast-flowing fluid removes the oxide film, thereby exposing the bare metal for further attack. Additionally, external vibrations may also lead to fatigue stress cracking, or to the tube's erosion at the point of contact with the baffles [1]. Heat exchanger failures can also be the result of fluid velocities exceeding safe operational limits, causing fatigue failures. Heat exchanger failure can also appear due to work hardening at the baffle contact points, or in U-bend regions, or adjacent areas until a fatigue crack appears. This occurs due to accumulated stresses associated with repeated thermal cycling, mainly due to the temperature differences across the length of the U-bend tube. When the stress exceeds the tensile strength of the tube, radial cracks develop. These can run around the tube, and sometimes cause a total breakdown [1,2]. In addition to the mechanical failures presented above, the continuous interaction of the heat exchanger tube material with the working corrosive fluid of specific temperature, velocity, pH, and hardness, can also cause the heat exchanger failures. Uniform corrosion is characterized by corrosive attack over the entire surface, or a large fraction of the tube's surface area, whereas localized corrosion generally results in the formation of pits. The mechanism behind the initiation and growth of such pits is attributed to the buildup of an electrochemical potential between the oxygen-rich areas (cathode) i.e. regions outside the pits, that generally remained un-attacked, and areas outside of the pits which are deficient in oxygen, therefore serving as the anode. This electrochemical potential sets up a concentration cell which leads to the continuous growth of pits, until they penetrate the entire tube. The pitting corrosion can be usefully prevented by eliminating surface defects such as scratches, or breaks in metal surface coatings, since these surface discontinuities triggers the onset of pitting corrosion, which ultimately leads to ultimate failures [1,2].

Apart from the basic mechanism of corrosion, there are more specific cases such as stress corrosion, which is a form of grain boundary attack. This is true, particularly in comparatively stressed regions, such as U bends. Galvanic corrosion is another form of a corrosion, in which an electrochemical cell, also known as a galvanic cell, forms between two dissimilar metals in contact with each other, in an electrolyte (acidic water). This generally happens when the heat exchanger tube is fitted with a turbulator spring, as in the present case. The less noble metal becomes the anode and therefore corrodes, while protecting the other one, which acts as a cathode that remains virtually un-attacked. A galvanic chart can be used to determine the potential between two metals. Another form of galvanic corrosion is "crevice corrosion". This occurs within crevices or hidden areas, for example, regions in-between baffles and tubes. Corrosion begins within these crevices, which eventually turn into pits. It has been observed that relatively stagnant conditions are conducive to crevice corrosion [2,3]. It is generally observed that heat exchanger failures are seldom occurring for just one reason. Typically, premature failures of heat exchangers are attributed to a combination of mechanical and chemically induced corrosion phenomenon and can occur in multiple locations at the same time. The two most common types are: erosion-corrosion, and corrosion fatigue. These failures are not very simple to identify, and generally require a detailed investigation [3-5].

Erosion-corrosion is accelerated corrosion due to the erosion of the protective film over the tube's surface, as a result of the sudden impact of high-velocity fluid, or suspended particles, on the surface of the tube. Additionally, mechanical vibrations can further aggravate the situation. Erosion-corrosion is observed near the tube entrance, a region where the tube and baffles meet each other, as well as at U-bend areas of a tube [3]. Corrosion fatigue, on the other hand, is an accelerated corrosion due to the stresses associated with fatigue, external vibrations from the external machinery, or thermal cycling (expansion and contraction of the tube). Generally, the buildup of the corrosion product inhibits further attack. However, cyclic stresses can break the oxide film, thereby exposing bare metal for further attack [5].

## Operating Parameters & Objectives of the Present Research Study

Brasses, the most common of the copper and zinc alloys, exhibit good mechanical strength, resistance to corrosion, and good thermal conductivity. As such, they are the candidate material for the fabrication of heat exchanger tubes, coolers, and condensers

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[6]. They are readily available, easy to machine/fabricate, and above all, are very cost-effective. However, their continuous exposure to an aqueous environment of a specific pH, conductivity, and hardness, will make them susceptible to pitting/dezincification [6,7]. Especially, the water circulating through these tubes, if contains a substantial amount of sulfate, nitrate, and chloride ions, together with an excess amount of carbon dioxide and oxygen, further enhances the corrosion rate. According to various studies, brass loses its resistance to pitting and can become prone to a dezincification process, when the zinc content exceeds 15%. However, the addition of tin and arsenic in brass can help in mitigating dezincification [6-8]. The present study aims to determine the possible causes for the failure of the leaking heat exchanger tubes made of red brass, equipped with a zinc-coated turbulator spring (AISI 1020) [9]. The turbulator spring was used to hasten the rate of heat removal, by inducing turbulence within the flow. The heat exchanger was a one-pass model with straight tubes. Treated water, at an operating pressure of 64 psi, was pumped through the copper tubes. These inlet and outlet temperatures were 47 °C and 57 °C, respectively.

On the external brass shell side, air/fuel mixture entered the exchanger at a temperature of 75 °C and was designed to leave the heat exchanger at 55 °C, before entering the engine, for achieving conditions needed for optimum combustion. The brass tube leakage was noticed after a service life of 12,000 hours, as compared to its recommended lifetime of 40,000 hours. The parallel arrangement of the tubes in the heat exchanger is shown in Figure 1a. The chemical compositions of the heat exchanger tube, and the turbulator spring, as determined by wet chemical analysis methods are given in Table 1.

**Figure 1:** (a) Parallel arrangement of brass tubes in the heat exchanger, (b) Tubes with the tube plate, arrowhead indicates the affected tube.

## Results & Discussion

Visual examination of one of the failed brass tubes was performed. This revealed a small pinhole on its surface, approximately 12 mm from the edge, as shown in Figures 2a & 2b. The size of the pinholes was approximately 0.5 mm in diameter. The adjacent areas of the tubes, around the pinholes, were observed to be bulged out, maybe due to the overpressure of water flowing through the tube (thermomechanical damage). No apparent surface defects were observed. However, when a similar pinhole, was analyzed from the inside of the tube, it appeared to be an irregular-shaped pit, length 1.2 mm and depth 0.7 mm., as shown in Figure 3. To investigate further, the brass tube was sectioned/flattened as shown in Figure 4 and analyzed under a stereomicroscope. Continuous pits/cavities were observed, specifically in those regions where the turbulator spring had been contacting the brass tube. These pits/cavities could have resulted from the erosion-corrosion phenomenon i.e. galvanic induced corrosion due to the two different materials, contacting each other (brass tube and turbulator spring), coupled with an erosion of the brass tube by the cyclic vibrations of the turbulator spring under operation, as shown in Figure 4. The distance between two consecutive pits/cavities equals the distance between two consecutive coils of the turbulator spring i.e. 7.5mm, running through the length of the brass tube, as shown in Figure 4. The hardness of the brass tube and turbulator spring is given in Table 2.

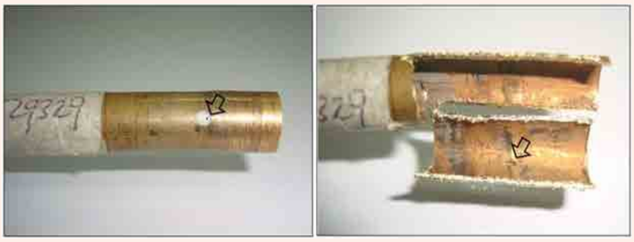

**Figure 2:** (a) As received brass tube showing a pinhole, 0.5 mm in diameter, (b) Sectioned brass tube, showing pinhole when viewed from inside.

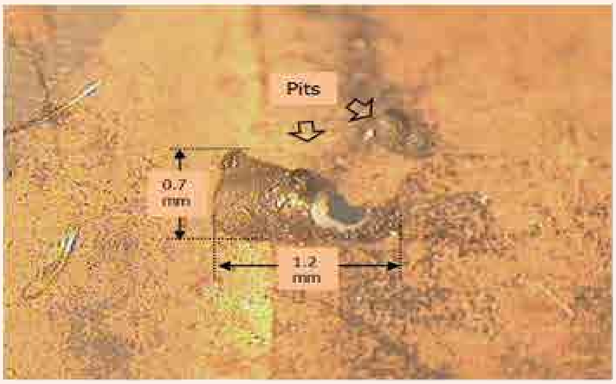

**Figure 3:** The inside of the tube, showing pits.

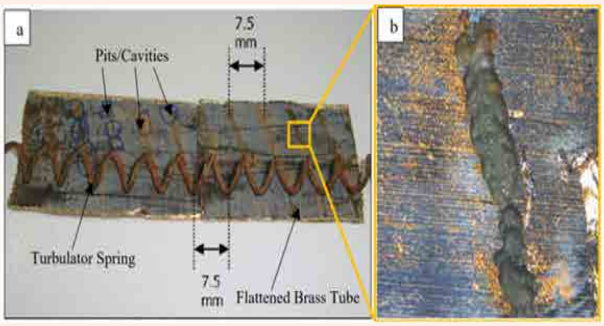

**Figure 4:** Adjacent portion of the tube, sectioned and flattened, showing continuous pits/cavities, running along the entire length of the turbulator spring, contacting the brass tube (20X).

**Table 2:** Hardness determination as per ASTM E140.

| Sample # | Measured Hardness | Converted Hardness |
|---|---|---|
| **Brass Tube** | 92±1 HV | 92±1 HV |
| **Turbulator Spring** | 49±1 HRC | 498±10 HV |

**Table 1:** Chemical composition analysis of brass tube, turbulator spring and steel shell.

| Sample | Chemical Analysis (Wt %) | | | | | | | | | | | Suggested Grade | Technique Adopted |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | Si | Mn | P | S | Ca | Cu | Zn | Pb | Al | Fe | | |
| **Brass Tube** | - | - | - | - | - | - | 84 | 15.9 | < 0.0 1 | < 0.0 1 | 0.05 | C23000 | Wet Chemical Analysis |
| **Turbulator Spring** | 0.57 | 0.22 | - | 0.013 | < 0.0 1 | < 0.0 1 | - | - | - | < 0.0 1 | | AISI-1060 | Wet Chemical Analysis |

## Metallographic Analysis

Metallographic examination was carried out to study the morphology and extent of the pits/cavities. These measured 0.2 mm deep and 0.7 mm wide, as shown in Figure 5. This corresponds to a loss of approximately 33% of the initial thickness of the tube i.e. ~0.6 mm. Concerning the grain structure of the material, the damage is smooth and trans-granular. The grain structure of the base tube is homogeneous as shown in Figure 5.

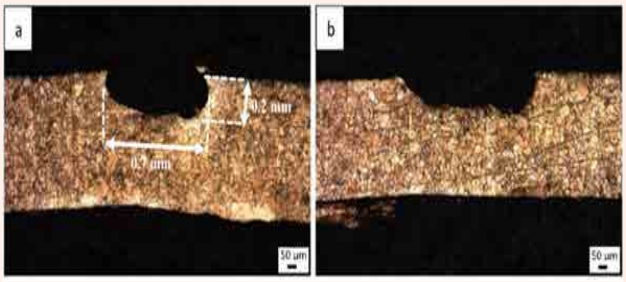

**Figure 5:** The cross-section of pits/cavities at two different locations, 50X.

## SEM/EDX Analysis

The brass tube was sectioned and analyzed using a Scanning Electron Microscope (SEM) (Figures 6 & 7). Additionally, Energy Dispersive Spectrometry (EDS) analysis was also carried out at various locations within the tube, as shown in Figures 8 & 9. As per the EDX analysis, Cu and Zn were identified as the principal alloying elements, in accord with the wet chemical analysis results presented above. Additionally, the pitted surface was observed to be depleted in zinc (de-zincification). Apart from the de-zincification of brass, traces of Ca, Fe, S, and P, were also observed to be deposited within these pits/cavities, as shown in Figure 8. Wet chemical analysis results (Table 3) have confirmed that these elements/compounds were present in the water, circulating through the brass tubes, and had accumulated over time. It is still unclear as to what extent they might affect the useful life of the heat exchanger, but they could have played a positive role in increasing the corrosion rate of the brass tube.

**Table 3:** Chemical analysis of water.

| Parameters | Actual |
|---|---|
| pH | 9.9 |
| Total Hardness as CaCO$_3$ | 6 |
| Calcium Hardness, as CaCO$_3$ | 4 |
| Total Alkalinity, ppm as CaCO$_3$ | 600 |
| Chloride, ppm as Cl | 60 |
| TDS, ppm/Conductivity, µS/square cm | 3000 |
| Silica, ppm as SiO$_2$ | Nil |
| Sulfate, ppm as SO$_4$ | Nil |
| Iron, ppm as Fe | <0.5 |
| Turbidity NTU | Nil |
| Suspended Solid, ppm | Nil |
| Free Chlorine, ppm as Cl | Nil |
| TPC/CFU | Nil |
| Nitrite | 1600 |

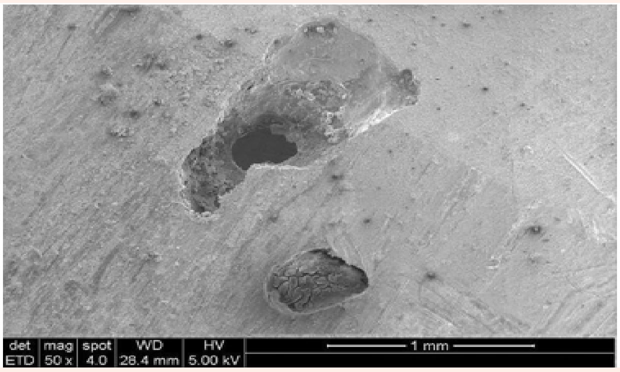

**Figure 6:** SEM micrograph from inside of the leaking tube (50X).

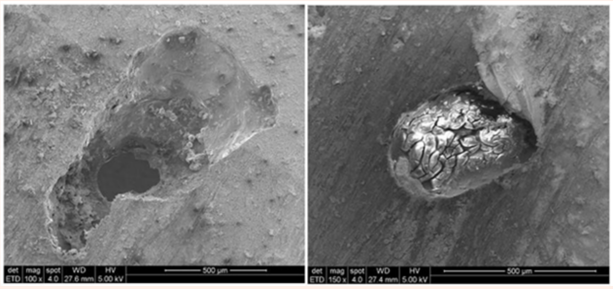

**Figure 7:** SEM image of the corrosion pit (a) large (100 X) (b) A pit covered with traces of Ca, Fe, S, and P deposits (150X).

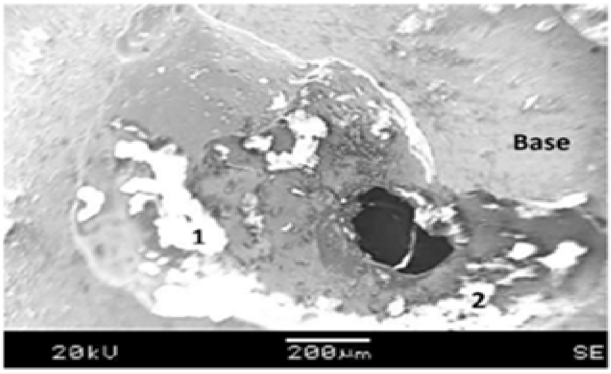

**Figure 8:** SEM Imaging/EDX analysis of the sectioned sample.

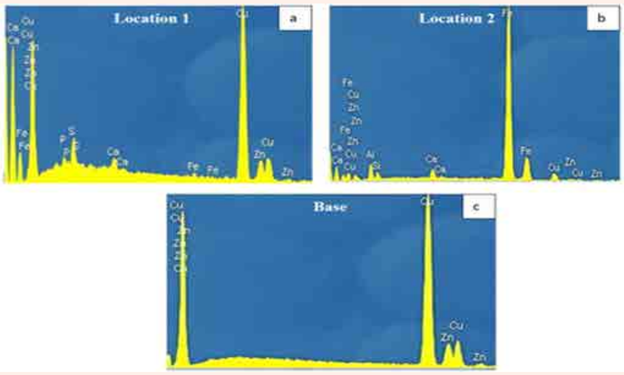

**Figure 9:** EDX spectrum at locations, marked as 1, 2, and base in Figure 8.

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## Conclusion

Continuous pits/cavities were observed, specifically in those regions where the turbulator spring was in contact with the brass tube. These pits/cavities could have been the result of erosion-corrosion phenomena i.e. galvanically-induced corrosion due to the two different materials, contacting each other (brass tube and AISI 1020 turbulator spring). This was coupled with an erosion of the brass tube as a result of cyclic contact of the harder turbulator spring (500 HV) with the soft tube (92 HV), i.e. in-service damage. Thermo-mechanical expansion of the tube resulted from the combined effect of the pressure build-up on the wall of the brass tube and to the temperature of the fast-flowing water, contributed to the failure, as well. Scanning Electron Microscope (SEM) and Energy Dispersive Spectroscopic (EDS) analysis indicated that the areas that suffered corrosion attack were depleted in zinc, in comparison to the bulk of the alloy.

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