Study of the failure of condenser tube in water cooled centrifugal chiller

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Abstract. Centrifugal Chiller is the most essential component of district cooling system. Intricate electromechanical design of the chiller leads to certain unanticipated and unpredictable failures, which affect the overall operational efficiency and reliability of the plant. A case study of unusual type of failure in centrifugal chiller serving district cooling plant has been discussed and presented in this paper. The main purpose of the study is to evaluate the underlying cause of failure of condenser tube. The study takes all possible failure assessments into consideration starting from visual inspection through hardness test, down to x-ray diffractometry. The end of the study demonstrates that the condenser tube leakage is principally attributed to impingement of miniature high velocity water jet at the small region inside the tube which removes the protective copper oxide film, thereby, making that area susceptible to corrosion. Entrapped vibrating foreign wire-like body with free end grinding against interior wall of the copper tube causes a similar damage to the protective film at the same area. Both effects resulted in a rarely reported type of erosion-corrosion phenomenon which finally causes the tube failure.

1. Introduction
Uncertainty exists widely in the design of district cooling systems. Due to failures, improper testing & commissioning and even unfitting maintenance of components or subsystems, the cooling systems may malfunction or work with reduced performance. In the conventional design method of district cooling systems, all aspects are often ignored or considered roughly [1]. Failure of centrifugal chiller serving district cooling plant is the most undesired event. The need for maintenance and the risk of down-time tend to be much lower when compared to the traditional distributed air conditioning system. District cooling systems can be operated at a high reliability [2] which some operating plants claim to have achieved up to 99.6%, equals to about 35 hours per year of downtime only. Implying that each subsystem making up the total system must be operated at higher reliability value. Therefore, it becomes a constant challenge to the operation and maintenance team to avoid any breakdown of components thus eliminating the risk of downtime of the system operation. However, at times, certain incipient failures creep-in which cannot be directly predicted or diagnosed. Leakage of condenser tube in the centrifugal chiller is one such failure. While the study of failure of heat exchanger tube is of great engineering interest in the industry, yet the failure presented in this study is of a unique type. The exclusiveness of
the case is palpable since the failure of tube in this study is finally attributed to Erosion-Corrosion [3] phenomenon. The failure of tube takes place in just two years of operating life. Specific to the case study, the symptoms of failure started when the operation and maintenance team observed unusual refrigerant pressure variation on condenser side of the chiller. The diagnostic carried out indicated the failure of tube. The leakage was immediately traced in the condenser tube which was plugged and isolated immediately. The initial characterization of the failure to corrosion alone was excluded as the condenser water chemical test report was showing the level of its constituents within or below the acceptable limit except total dissolved solids (TDS) which was slightly higher. The failure of one tube on condenser side could have proven catastrophic to the district cooling plant if other tubes on remaining 13 modules of chillers were similarly affected and damaged. Therefore, a high-level detailed study was initiated to rule out the possibility of same failure on other tubes in remaining chillers. Detailed examination and appropriate testing of the failed tube were undertaken. All the four criteria that were set for finding actual cause of the problem. Starting from visual inspection through Vickers hardness test [4] to elemental analysis using x-ray diffractometry [5], all test results have been found interrelated and funneling down to common conclusion that the failure was indeed due to erosion-corrosion effect.

2. Input information to the study
Following information has been considered as initial inputs to the study.

2.1 Technical Specifications of the Chiller unit

1. Chiller Tag: CH-06
2. Cooling capacity per module: 2562 Tons of Refrigeration (TR)
3. Chilled water Specifications: Inlet Temp, $T_i=13.77\, ^\circ C$, Outlet Temp, $T_o=8.81\, ^\circ C$, $1559.3\, m^3/h$
4. Condenser water specifications: Inlet Temp, $T_i=38.3\, ^\circ C$, Outlet Temp, $T_o=41.75\, ^\circ C$, $2722.6\, m^3/h$
5. Refrigerant: R134a
6. Failed tube designation: H8V26 / condenser

2.2 Thirty-one (31) Months Operational Data
The district cooling plant has been functional since 2012. The operational detail of each equipment has been obtained. The operational data which indicated the key interest parameters was obtained for the plant with following details:

a. Duration of Data: January 2013 to July 2015. Failure observed around December 2014 and Jan 2015.
b. Parameters captured: Kilo Watt Hour (KWh) of Chillers, Primary Pumps, Secondary Pumps, Condenser Pumps, Cooling towers, and other components.
c. Tons of refrigeration hours (TRH) Generation of all six (06) chiller units was obtained to find out if the chiller in subject study was into operational since the first start up.
d. Total TRH of the plant obtained.
e. Overall Kilowatt per Ton (KW/TR) index of district cooling plant (DCP) was obtained.
f. Figure 1 shows the operational tons of refrigeration hour (TRH) generated by the subject chiller unit. This data is important since it indicates the working hours of the chiller in consideration.
g. Chemical test report of secondary and condenser water side obtained. For condenser water, only total dissolved solid was higher than recommended. Rest all other parameters were normal.
h. Design data with limited parameters obtained.
i. Load profile and percentage of total run time for chillers not provided.
j. Figure 1 shows the operational log in terms of tons of refrigeration generated. This log is of less importance from study point of view, yet it provides information on when the equipment was in duty.
Figure 1: Operational history of Chiller (CH-6) in terms of tons of refrigeration generated

2.3 Failed component details
a. Failed component is copper tube on condenser side.
b. Material of Copper tube is phosphorous deoxidized copper
c. Location H8V26 as shown in the figure 2.

Figure 2: Location of the failed condenser tube.
3. Study and investigation criteria
Following are the items that form test criteria for the study of the case.

Table 1: Criteria matrix used for investigation into finding cause of failure of the condenser tube

| SN | Criteria                              | Items under study                  | Details                                                   |
|----|---------------------------------------|------------------------------------|-----------------------------------------------------------|
| 1  | Visual Inspection                     | Failed Tubes H8V26                 | For checking the location of failure due to leakage and macroscopic examination |
| 2  | Cut away hemi cylindrical section details | Failed Tubes H8V26               | For revealing the details of the leakage part and possible agent of external force. |
| 3  | Hardness Test                         | Failed Tubes H8V26                 | To study the hardness at leakage area and possible mechanical deformation. |
| 4  | Chemical Study                        | Failed Tubes H8V26 Chemical Analysis of ash grey deposit | For identification of the inner deposits and Foreign body |

4. Details of the Criteria
Each of the investigation criteria as per table 1 is detailed as follows:

3.1 Visual Inspection.

3.1.1 Leakage area

The images of tube H8V26 are shown in figure 3 with details of each sections. The images show both exterior and interior magnified views of the tube at and around the leakage area. The exterior view in the magnified image shows a slot type opening or damage across the wall thickness. This slot opening is further clearly seen in the inside cut-away section of the hemi-cylindrical fragments of the tube. It can also be seen that in the local area of leakage, the sides of slot opening do not have protective copper oxide film visible. Therefore, it can be implied that near the leakage part of H8V26, the inner surface should have been exposed to mechanical grinding, as the surface showed metallic luster.

3.1.2 Deposit and foreign material inside the tube

Figure 4 shows further images of H8V26 Tube. Material recovered around the leakage area in the form of wire pieces and ash like grey deposit. The bonding of the long wire piece with the ash like deposit was such that one side of the wire was firmly attached to the ash whileas other side was free to move or oscillate. Moreover, the free side of the wire was coming in the path of opening in the ash deposit which would have been the flow of stream of condenser water. Due to restriction in flow area, the velocity would rise in said path and the jet of water would impinge on the free side of wire. It was interesting to find from figure 3 that the slot opening in the tube is somewhat on opposite side of the wire. Which leave enough clue that vibrations of this wire could have resulted in miniature hammering action or grinding action on the interior side of the tube which has removed the protective copper oxide film.
Figure 3: Images of H8V26 Tube at and around the leakage area. Both exterior and interior views.

Figure 4: Images of H8V26 Tube around leakage area. Foreign material (wire like) and grey lump of deposit (ash like) detailed.

Figure 4i: Wire like material removed from H8V26 near leakage area

Figure 4ii: Lump of grey deposit obtained at and around the leakage area
### 3.2 Cross Sectional Microstructure Observation

The cross-sectional microphotograph of the leakage part of tube H8V26 is shown in figure 5. The metallographic structure [6] of the inner surface near the leakage part was crushed and distorted remarkably like the surface which received mechanical grinding. The micrographs included below range from 400 micrometre down to 20 micrometre. The slot opening around the leakage part is the region of interest in this case. Visualizing the metallographic structures from the inner and outer sides of the tube around the leakage area has been considered and included in the figure 5. In the leakage part, the thinning morphology which shows that thinning is progressing toward the outer surface from the inner surface was observed. Deformation of metallographic structure due to mechanical force was not observed in the thinning part except for the fin machining part.

![Figure 5: Micrographs of the leakage area of H8V26 Tube](image)

### 3.3 Hardness test

The result of hardness test by micro Vickers near the damage part of tube H8V26 is shown in Table 2. The measurement point is shown in Figure 6. The hardness near the damage part was equivalent to the hardness of general part.

![Figure 6: Hardness Test Target points H8V26](image)
Table 2: Result of hardness test of tube (Micro Vickers, weight 10g)

| Measurement point of hardness test | Hardness (HV0.01) | Average |
|-----------------------------------|-------------------|---------|
| [1]                               | 107               | 111     | 108     | 109     |
| [2]                               | 121               | 120     | 117     | 119     |
| [3]                               | 112               | 108     | 113     | 111     |
| [4]                               | 109               | 109     | 112     | 110     |

3.4 Chemical analysis

The results of elemental analysis of inner deposit and foreign body near the leakage part of tube H8V26 are shown in Table 3. The results of identification of chemical composition (by XRD) [7] of inner deposit near the leakage part of tube H8V26 is shown in Table 4. As a result, it was revealed that the main element of the deposit is Ca (calcium) and the main component of the deposit was identified CaCO₃ (calcium carbonate) generally known as calcareous deposit in cooling-water system. The main elements of the wire shaped foreign body were Fe (iron), Cr (chrome), and Ni (nickel).

Table 3: Elemental Analysis of inner deposit and foreign material

| Subject                       | Element content (weight % ratio) |
|-------------------------------|---------------------------------|
|                               | Na    | Mg    | Al    | Si | P | Cl | Cr | Mn | Fe | Ni | Cu | Zn |
| Wire Shaped Foreign Material  | -     | -     | -     | -  | - | -  | 2x10¹| 1  | 7x10¹| 9  | -- | -  |
| Inner Deposit                 | -     | 2     | 2     | 5  | 1 | 1  | 8x10 | -  | -  | 4  | -  | -  |

Table 4: Identification and result of the inner deposit of tube

| SN | Item          | Chemical Composition           |
|----|---------------|--------------------------------|
| 1  | Inner Deposit | CaCO₃ (Calcite)                |
|    |               | Amorphous Compound            |
4. Evaluation of the cause of leakage

The results of study conclude that the failure of tubes cannot be attributed to mechanical forces which could have existed in the system due to over pressurization of the condenser line water. Moreover, the condenser pumps on the district cooling plant is designed to operate at the dynamic head of 30m which equals to the 294.12Kpa which is much below the pressure that can rupture the copper tube. Copper exhibits the property to form the anti-corrosive and self-protective precipitation of copper oxide film [8]. This film cannot be removed unless high impinging velocity exists in the fluid flowing in the tubes. As per section 3.1.2, it was seen that area restriction exists due to the deposition of calcium carbonate which would give rise to the velocity of water such that it is enough to remove the protective copper oxide film [9]. Also, due to entrapment of wire shaped material, fixed on one end and free on the other end, as per section 3.1.2, such rattling motion of the free end could have contributed in removal of copper oxide film and exposed the metal to corrosion. Conclusively, the failure of the tube under study is due to the combined effect of erosion-&-corrosion. Detachment of copper oxide film due to high water velocity and grinding local effect foreign body is the root cause of the tube leakage. Moreover, the deposit in the form of oxide scale and the surface at the time of leakage were removed, the evidence which can specify the cause of leakage is not able to be found out. The coolant water is alkalescence and concentration of hardness composition or suspended solids are relatively high, and the scale containing calcium carbonate [10] may deposit easily under this coolant water. Therefore, this coolant environment may have the risk of failure due to deposition of foreign body [11].

Although the failure of evaporator and condenser tubes has been at the centre of engineering studies [12] of component failure, yet this case study present a unique phenomenon of erosion-corrosion which is least observed to be the cause of failure in case of chiller condenser tubes. This case study also indirectly lays high emphasis that the start-up, commissioning and maintenance of the chillers must be carried out with good workmanship. If the annual preventive maintenance of tubes using tube clearer was carried out with proper skill and technique, this failure could have been avoided.

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