Failure Analysis and Optimisation of Tube Water Cooler of Hydropower Plant

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Abstract-- **A shell and tube cooler is used to cool the cooling water of oil cooler. This cooling water of the oil cooler cools the oil that lubricates the generator thrust and guide bearings, turbine guide bearing, and the governor oil sump tank at a hydroelectric unit, in a closed system. Cooling water is treated water while a cooler fluid in shell and tube is raw water with an open circuit. The debit of treated water and raw water is 37.8 m^3/hr and 54m^3/hr respectively. Allowable pressure drop for the two fluids is 1.6 mWS for treated water and 0.3 mWS for raw water respectively. Treated water flows through the tube side with inlet and outlet temperatures of 42°C and 38°C, whilst the raw water flows through the shell side with inlet and outlet temperatures of 30°C and 32°C. The cooler tube is made of copper with a purity of 99.9%, and is designed to operate for 5 years. The shell and tube cooler has been in operation for 2 years and suffered damage (leaks) in tubes under the shell inlet nozzle, in the top row. Damage in the form of a large tear having with local deformation, corrosion and fouling was observed. To find the cause of the damage a number of laboratories testing on tube material samples and raw water samples has been performed. The tests performed included the microstructure and mechanical properties examinations, water quality testing, corrosion and its rate of growth. In addition to laboratory tests, a cross-flow velocity calculation has also been made. From the tests of fluid, it has been found that most likely the damage was caused by the tube cross-flow velocity, the condition of the water as a cooling medium which is corrosive and erosion-corrosion impingement phenomenon and erosion-corrosion pitting.**

1. INTRODUCTION

Lubricant cooling systemon a hydropower consists of two circuits as shown in Figure 1.1

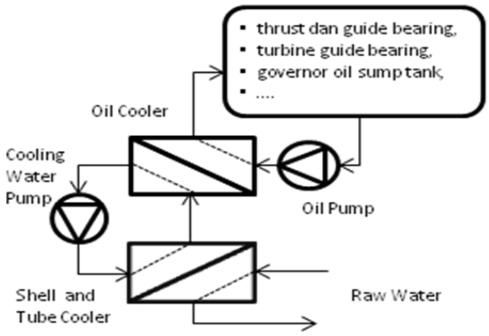


Fig. 1.1. Lubrication system on Hydropower

An oil cooler is used to cool the oil that lubricates the generator thrust and guide bearings, turbine guide bearing, and the governor oil sump tank at a hydropower unit. As the cooling medium in the oil cooler is used treated water in a closed circuit. Furthermore, the treated water is cooled in a shell and ttube cooler using raw water as a cooling medium with an open circuit. The flow rate of treated water and raw water are 37.8 m^3/hr and 54m^3/hr respectively. Allowable pressure drop for fluids flow, 1.6 mWS for treated water and 0.3 mWs for raw water respectively. Treated water flows through the tube side with temperatures in and out of each 42°C and 38°C, whilst the raw water through the shell with the temperature in and out of each 30°C and 32°C. Tube is made of copper with a purity of 99.9%, and is designed to operate for 5 years. Until now, shell and tube cooler has been operating for 2 years and have suffered damage (leaks) in tubes under the shell inlet nozzle form a large tear, tube locally deformation in the top row, corrosion and fouling. It is estimated that the damage caused by the cross-flow velocity, the condition of the raw water as a cooling medium which is corrosive and erosion-corrosion impingement phenomenon and erosion-corrosion pitting.

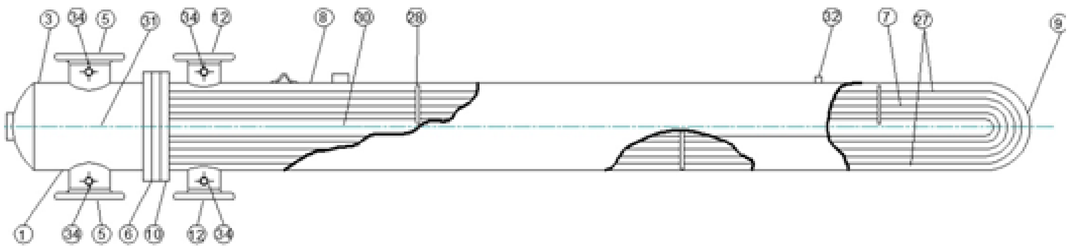
Damage to the shell and tube cooler has led to the unplanned shutdown of hydropower and damage other equipment so as not to produce electricity and cause greater losses. To determine the cause of the failure, analysis and testing has been done on the sample tube material to determine the microstructure and mechanical properties, water quality, corrosion and its growth rate, calculate the cross-flow velocity, and then verifies the data and specifies the type of the test results and the type of damage.

1.1. Shell and Tube Cooler

Shell and tube heat exchanger consists of a bundle of tubes enclosed in a cylindrical shell. The ends of the tubes are fitted into tube sheets, which separate the shell-side and tube-side fluids. Baffles are provided in the shell to direct the fluid flow and support the tubes. The assembly of baffles and tubes is held together by support rods and spacers.

In the context of shell and tube cooler on a hydropower show in Figure 1.2, this equipment serves to cool the cooling water from a hydropower plant lubrication system. Cooling water from oil cooler flows in the tube side and the raw water as a cooling medium flows in the shell side. The principle types of shell and tube exchangers classified by

TEMA Standards [1]. According to [1] the geometry of the construction of this shell and tube cooler is BFU, having equilateral triangular tube arrangement, with single transverse segmental baffles as shown in Figure 1.2 and 1.4.



Note:

1. Stationary Head-Channel, 3. Stationary Head Flange-Channel or Bonnet, 5. Stationary Head Nozzle, 6. Stationary tube-sheet, 7. Tubes, 8. Shell, 9. Shell Cover, 10. Shell Flange Stationary Head End, 12. Shell Nozzle, 27. Tie-rods and Spacers, 28. Transverse Baffles or Support Plates, 30. Longitudinal Baffles, 31. Pass Partition, 32. Vent Connection, 34. Instruments Connection,

Fig. 1.2 Main Components of Shell and Tube Water Cooler U13A/1-2-2, [2]

1.2. Damage Location

From visual observation, the location of the damage is on the first raw of the tube just below the shell inlet nozzle (see Figures 1.3 and 1.4). This damage may be caused by a shell inlet nozzle ρV^2 exceed the allowable value.

Fig. 1.3. Photos of the damaged tube [2]

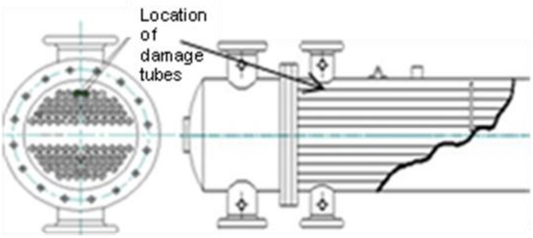


Fig. 1.4. Schematic location of the damaged tube

TEMA Standard stipulates that the protection required by the impingement plate where ρV^2 in shell inlet nozzle exceed the values given in Table 1.1 [1].

1.3. Corrosion of Copper

- **Definition of Corrosion**

Corrosion is the damage that occurs when metal reacts with its environment, there is a transfer of electrons or galvanic interaction between the anode (active) and the cathode (passive) in the electrolyte, and occurs when an independent energy compounds decreased to a negative value [3].

TABEL 1.1
TEMA IMPINGEMENT PROTECTION CRITERIA

Type of Fluid	ρ (kg/m³) V (m/s)	ρ (lb/ft³) V (ft/s)
Non corrosive, non abrasive, single phase	2230	1500
All other liquids, including liquid at its boiling point	744	500
All other gases, vapors, saturated vapor and liquid-vapor mixtures	0	0
Where :ρ=mass density of liquid V= velocity of fluids		

Corrosion can also occur when the metal is exposed to oxygen or halogens. Copper is a product that truly passive corrosion. In the water environment which has an average temperature around 40 ° C, the product of corrosion is caused by copper oxide (Cu_2O). Copper oxide is a p-type semiconductor formed by an electrochemical process (Figure 3.5). For the corrosion reaction, copper ions and electrons must migrate through Cu_2O films which can consequently reduce the ionic or electronic conductivity of the film by doping with divalent and trivalent cations should increase corrosion resistance (Figure. 1.5). [4]

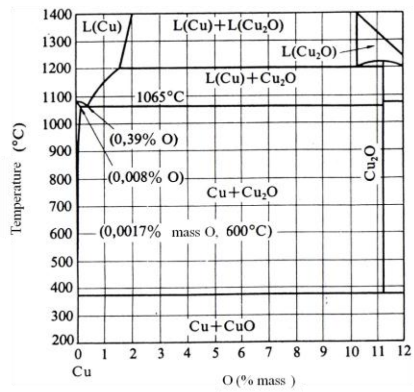


Fig. 1.5. Phase diagram of Cu-O

In practice, the addition of elemental zinc, tin, iron, and nickel are used to reduce the corrosion rate significantly.

There are various types of corrosion that can occur in copper contact with water, i.e. [5]: Corrosion surface, well, etc (see Table 3.1). However, from the observation, in the case of damage to the tube water cooler corrosion-erosion is likely more dominant. The explanation of the mechanism of the formation of corrosion-erosion is as follows:

- Mechanism A (Mechanical-Chemical Problem or Erosion-Corrosion Problem):
  Fluid flow is not containing abrasive particles (free of abrasive particles). However, the cross, and the turbulent flow because of the unevenness of the surface (surface discontinuities) so that film coating peeling produce surface unevenness is getting worse, and cause corrosion and erosion phenomena (due to increased turbulence) locally.
- Mechanism B (Problem Mechanical or Particle Erosion Problem):
  Fluid flow is containing abrasive particles. The collision of solid particles can damage the protective oxide film continuously when there is friction with fluid (fluid shear) so that film coating peeling. This phenomenon produces surface unevenness is getting worse, so the angle of collision of solid particles of more than one direction. Besides the collision and the velocity of flow, hardness of solid particles also determines the level of erosion.

2. METHODOLOGY

The study includes a visual inspection, sampling water and tube material, collection of operations data, material and water quality testing.

2.1. Visual Investigation

Visual inspection is necessary before a more detailed testing was performed. This examination is conducted to analyze the material surface defects and associated operating conditions that are likely as a major cause of damage to the water cooler tube.

2.2. Water Samples and Damage Tube Sample

In this shell and tube cooler, hot water coming from oil cooler circulates in the tube side and the raw water from the reservoir (cold water) to flow in the shell side (in open loop) dumped directly into the ttailrace. Raw water as a cooling medium having a material impact on the copper tube water cooler. Corrosion is influenced by the nature of the metal or alloy and its environment, in particular: the pH (acidity), oxidizing power (potential), temperature (heat transfer), velocity (fluid flow), and concentration (solution cconstituents). Water sampling procedure for referring to the SNI standard and the regulation of Minister of Health of the Republic of Indonesia Number 416/MENKES/PER/IX/1990. The sampling tube test for material testing performed on tubes that were damaged by the ASTM standard.

2.3. Design Sheet

Design sheet and detail drawing of shell and tube cooler should be available to perform the analysis of the causes of damage and evaluate the design of a follow-up of the damage.

2.4. Metallographic testing

Metallographic testing aims to determine the properties of metals and alloys by micro structural shapes, analysis material defects or irregularities of the metal structures and. Metallographic tests conducted using ASTM E407-93 test method for Cu tube material in the damaged area to obtain the microstructure of Cu samples.

2.5. Hardness testing

Hardness testing aims to determine the change in hardness on tube material that has been damaged. Hardness testing carried out following the microstructures test was used. The magnitude of the compression force used can be selected from 1 to 120 kg, depending on the hardness / thickness of the test material in order to obtain an easy tap traces measured.

2.6. Examination of the chemical composition of the tube material and the raw water

Chemical composition analysis of the tube material is performed to determine whether the material in accordance with design specifications tube cooler. Tools used for the examination are optical emission spectrometer. Examination of the chemical composition of cooling water (raw water) aims to determine the types of dissolved solids and other substances present in the water.

2.7. SEM testing

SEM testing aims to determine the damage topography and the damage propagation due to surface oxidation, corrosion products, and contaminants and form a certain texture. Testing was conducted on Cu tube material in areas that were damaged.

2.8. EDAX testing

EDAX testing aims to analyze the chemical composition of surface and deposit that may have formed on the damage surface of the cooler tube being investigated

2.9. Samples for Testing Materials

For the purposes of the material test, the sample of material is taken at damaged tube (the shell inlet nozzle area, tube top row) as shown in Figure 2.1 and 2.2.

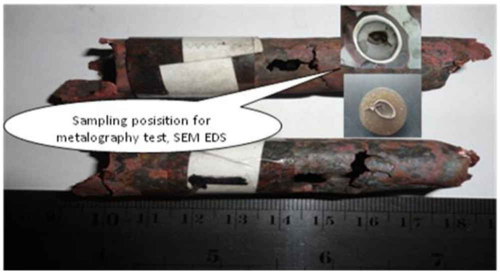


Fig. 2.1. Samples for Testing Materials

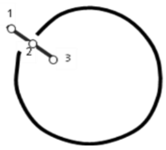


Fig. 2.2. Scheme of sampling points for metallographic test SEM and EDS

3. RESULT AND DISCUSSION

3.1. Initial Hypothesis

Based on visual data (Figure 1.3), damage in the form of a large tear, local deformation due to the depletion of materials, corrosion and fouling presence is present. Initial analyzes of the damage is as follows:

a. The damage was not caused by the phenomenon of flow-induced vibration (vortex shedding, turbulent buffeting, fluid-elastic whirling, ..) that can cause damage in the form of collision damage, baffle damage, fatigue, tube joint failure as usually shown in Figure 3.1

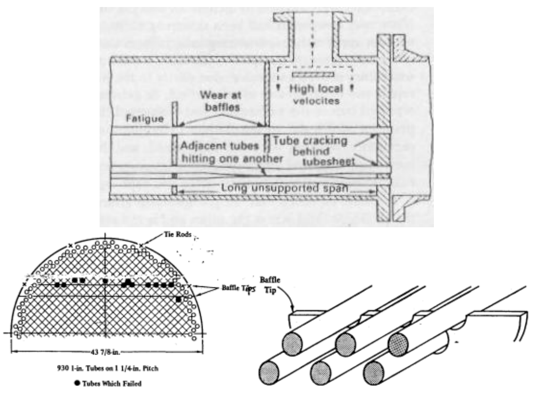


Fig. 3.1. Location of Damage [6]

b. The damage seems to be more due to the cross-flow velocity of the shell inlet nozzle with a high ρV^2 that may result impingement on the tube surface so it can peel the protective film from the copper tube surface. This phenomenon will bring the corrosion layer, causing the initial formation of surface corrosion and erosion corrosion.

c. Corrosive cooling water flowing on the surface of the tube, followed by the rate of corrosion of the tube to form corrosion-erosion and fouling resulting in depletion of the tube walls and locally deformation that may subject the tube surface to become leaky.

3.2. Calculation of ρV^2

Operational and geometry data shows that the average flow rate of raw water in the shell side is about 14.93 kg/s, the shell inlet nozzle diameter 114.3 mm (DN 100 PN 16), shell inlet temperature 30^{o}C, and the shell inlet pressure 15 bar. From these data, can be obtained density of water ρ = 995.42 kg/m^3, shell inlet nozzle velocity V = 1.46 m / s, and ρV^2 = 2127 Pa. From Table 1.1 this ρV^2 is much greater than the data for the requirements of the corrosive and abrasive liquids (744 Pa)

3.3. Raw Water Analysis Results

The results of the chemical analysis of the samples of raw water in the shell side are shown in Table 3.1.

TABLE 3.1
RESULT OF RAW WATER TESTING (SHELL SIDE)

No	Parameter Analysis on the Depth 8 m	Unit	Quality Standards Max	Test Resuts
1	Ammonia-Free	mg/L	0.02	0.001
2	Sulfate (SO_4)	mg/L	400	27
3	Turbidity	NTU	7.19	6.15
4	BODs	mg/L	6	4.05
5	Nitrite-N (NO_2 – N)	mg/L	0.06	0.01
6	Mangan (Mn)	mg/L	0.5	0.04
7	Iron (Fe)	mg/L	5	0.13
8	PH	-	6-9	6
9	Chloride (Cl)	mg/L	600	14.4
10	Sulfide as H_2S	mg/L	0.002	0.01
11	Dissolved Oxygen (DO)	mg/L	3	7.25
12	COD	mg/L	10	10.52
13	Nitrate – N (NO_3-N)	mg/L	10	0.19
14	Zinc (Zn)	mg/L	0.02	0.005
15	Dissolved Solids (TDS)	mg/L	1000	280
16	Temperature	^{o}C		26

3.4. Test results of material

a. Material Tube Chemical Composition and Hardness Testing Results

From the test results of the copper tube material obtained, it is found that the composition Cu 99.9% and the rest are other elements as shown in Table 3.2, with the hardness properties 0.5 kg_f/mm^2.

TABLE 3.2
TESTING RESULTS SPECTROMETRY 126 414

Material		:	Cu					
Date		:	4/11/2012					
Method		:	Cu - 01					
Comment		:	Orientation Cu-base					
Zn	Pb	Sn	P	Mn	Fe	Ni	Si	Cu
0.0047	0.003	0.0018	0.0355	0.0002	0.0049	0.0022	0.05	99.9

b. Metallographic Testing Results

Metallographic ttests conducted on Cu material in a damaged area using ASTM E 407-93 test method. The test results are known Cu sample microstructure consists of matrix-α. Seen also any indication of corrosion damage and corrosion erosion surface, as shown in the following figure (Figure 3.2 – 3.6)

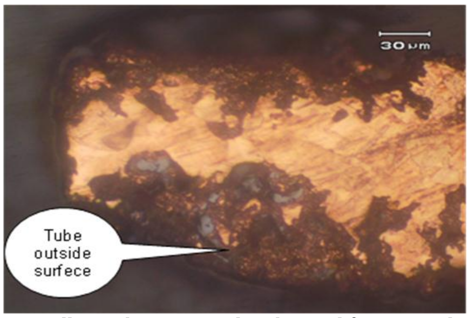


Fig. 3.2. Metallographic test results obtained from sampling point 1(Etching: 2gr K_2Cr_2O7 + 8 ml H_2SO_4 + 4 ml saturated NaCl _100 ml H_2O).

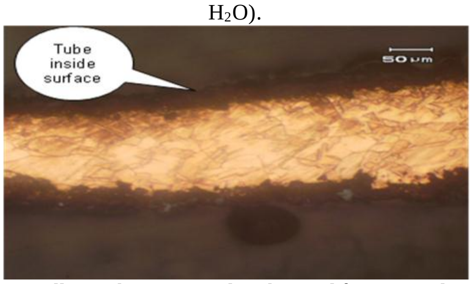


Fig. 3.3. Metallographic test results obtained from sampling point 2 (Etching: 2gr K_2Cr_2O7 + 8 ml H_2SO_4 + 4 ml saturated NaCl _100 ml H_2O).at

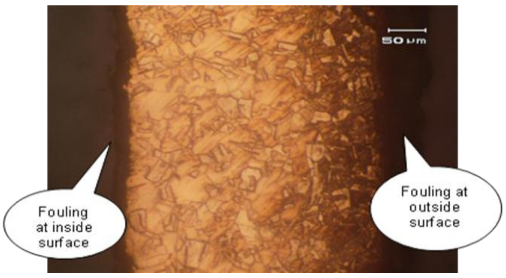


Fig. 3.4. Metallographic test results obtained from sampling point 3 (Etching: 2gr K_2Cr_2O7 + 8 ml H_2SO_4 + 4 ml saturated NaCl _100 ml H_2O).

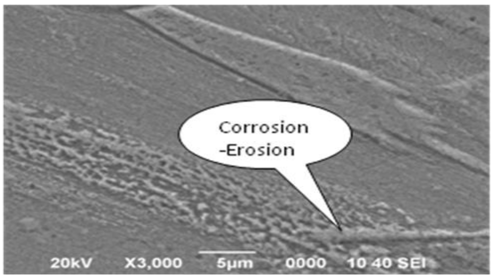


Fig. 3.5. SEM micrograph obtained from sample 2

From the results of SEM and EDAX test for sample 2, found elements of O and Cu respectively 1.3% and 98.7% in percent of mass.

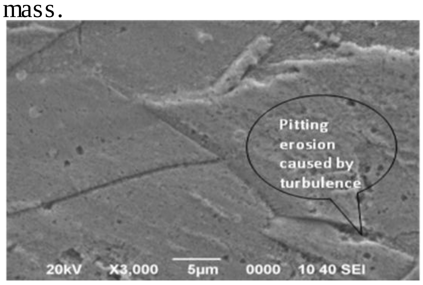


Fig. 3.6. SEM micrograph obtained from sample 3

From the results of SEM and EDAX test for sample 3, found elements of C, O and Cu respectively 11.6%, 24.3% and 85.16% in mass percent

3.5. Discussion

Most tube damage occurred in the first row under the shell inlet nozzle (Figure 1.3). From the type of damage, it is not caused by flow-induced vibration, but caused by the ρV^2 at the shell inlet nozzle exceed the permitted values (see Table 1.1). Besides the mechanical factors, tube damage also occurs due to erosion-corrosion attack, (the reaction between the copper tube and the water as a cooling medium).

The mechanism of the erosion-corrosion damage can be seen schematically in the fishbone diagram (Figure 3.7).

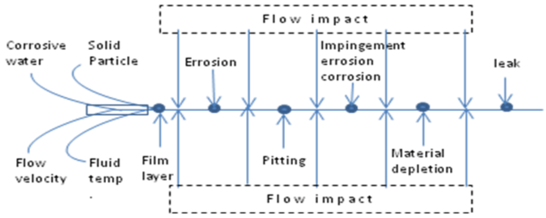


Fig. 3.7. Mechanism of erosion-corrosion tube damage

Corrosive water containing solid particles (see Table 3.1) which flows through the shell inlet nozzle at high speed, hit the first line of the tube surface. This causes the film coating (corrosion reaction product) should be formed, had drifted due to flow velocity.

Peeling of film coating on the surface of the tube and continuous collision resulting in a rough surface and is a beginning of the erosion-corrosion. This phenomenon causes pitting corrosion-erosion (Figure 3.5 and 3.6). This event took place repeatedly resulted in depletion of tube surface, and leakage. The explanation that the film should be formed when copper corrosion reaction present is shown from the results of metallographic tube samples that are stored in atmospheric conditions (Figure 3.4).

From the above discussion the type of corrosion that occurs the copper tube can be classified as shown in Table 3.2.

TABLE 3.2
IDENTIFY THE TYPE OF CORROSION ON TUBE

Literature Study /ASM Handbook, 1992/			Discussion of Test Result
No	Corrosion Type	Indication	
A	Surface Corrosion	• Occurs evenly on the surface • Metal thinning evenly	• Surface corrosion occurs • From visual observation and metallographic test, the biggest depletion of the surface of the pipe and focus occurred in the shell inlet nozzle due to the high cross velocity
B	Pitting Corrosion	• Uneven gap occurs in the form of pits • Corrosion pitting occurs in the metal is in an environment containing chlorides and sulfides	• Figure 3.6 indicates pitting corrosion occurs
C	Crack corrosion	• Occur at the inter stices • Inter stices between the metal surface and the scaling	• No corrosion occurs
D	Galvanic corosion	• Occur when two different metals ar interconnected • The less noble metal will corrode faster	• There are indications of galvanic corrosion occurs because there are enough elements Fe found at cooling water.
E	Intergranu lar Corrosion	• Occurs at grain boundaries or aroung grain • Grain boundaries are	• From the results of metallography test and SEM test, no strong indication of intergranular

		cathodic	corrosion
G	Selective Corrosion	• Occurs when one component phase elements in the alloy is a solution or corroded. Exemple; dezincfication on brass	• Selective corrosion occurs on the surface of tube (see Figure 3.4)
H	Errosion-corrosion	• Combination destruction occurs in the form corrosion and erosion of metal by fluid flow • Abrasive particles that will erode the oxide layer so that the protective layer loss and the corrosion process will be faster	• From Figure 3.5 there appears to be abrasion and erosion of metal by fluid flow. • From the test water sample known to many abrasive particles, including the type of corrosion mechanism B
I	Fatigue corrosion	• Damage caused by a combination of mechanical (fatique) and the environment (corrosive) so the damage becomes faster	• There is no indication of corrosion fatigue

4. CONCLUSIONS AND SUGESTIONS

4.1. Conclusion.

Based on the results and discussion above, it can be concluded that the mechanism of damage occurred on the water cooler tube is as follows:

a. Flow velocity at the shell inlet nozzle around 1.46 m/s produced in the shell inlet nozzle ρV^2 exceeds the permitted values.
b. Corrosive water containing solid particles flows through the shell inlet nozzle at high speed, hit the first row of the tube surface. This causes the film coating (corrosion reaction product) that should be formed had drifted due to flow velocity.
c. Peeling of film coating on the surface of the tube and continuous collision resulting in a rough surface and is a beginning of the erosion-corrosion. This phenomenon causes pitting corrosion-erosion to occur
d. This event took place repeatedly resulted in depletion of tube surface, and finally tube leakage

4.2. Suggestion

From the results of this study it can be recommended for the prevention or correction of damage which include:

4.2.1. Control of mechanical damage:

a. Installation of impingement plate as shown in Figure 4.1.
b. Constant flow velocity setting.

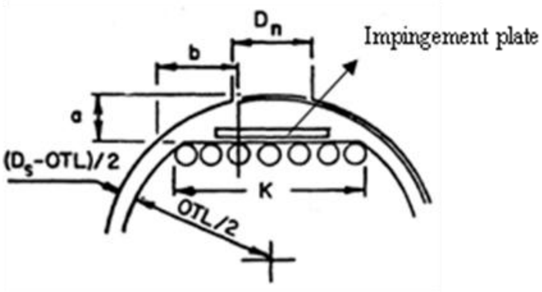


Fig. 4.1. Impingement Plate – Partial layout [1]

4.2.2. Corrosion Control and maintenance cooling water quality:

a. Control the corrosiveness of cooling water by adding corrosion inhibitors
b. Perform routine maintenance techniques in accordance with the requirements of the operation and maintenance
c. Perform routine control of chemical composition of cooling water to keep it meets quality standards.

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