A STUDY ON THE DESIGN OF THERMOSYPHON EVAPORATOR USED IN NUCLEAR WASTE VOLUME REDUCTION METHOD

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ABSTRACT

The volume of High-Level Liquid Nuclear Waste (HLLW), produced during the operation of reprocessing of nuclear waste is very high. These wastes may contain radioactive elements such as Cs, Sr, U, Pu, Ru, etc, Along with their isotopes and many other harmful elements. These HLLW from the plant were sent for permanent storage. The quantity of the waste is high if stored in the waste vault; it required larger tanks and constant surveillance. In this study Thermosyphon evaporator was designed to reduce the volume of the HLLW, and by introducing evaporation process before storing the nuclear waste the study highlights that the total volume is reduced half the original volume. This process of evaporation reduces the total volume to half of its original value with the limitation of its acidity not exceeding 6. Since it is the maximum limit at which the corrosion level is optimum of lesser than 15 mills per year and it exceeds drastically at higher acidity.

Key words: Nuclear waste, Volume reduction, Evaporation, Thermosyphon evaporator

INTRODUCTION

During the operation of the nuclear process they generate two types of wastes they are high-level waste and low-level wastes. High-level waste consists of spent fuel, fission products and transuranic materials generated during the fission reaction. Low-level wastes are filters, resins used for purification.¹ Waste processing methods are employed for the recovery and handling of noble metals one such method which is suggested by many researchers is volume reduction.² The various processes available for volume reduction are Evaporation method, Ion exchange Method Reaction with formaldehyde under the boiling condition, Reaction with formic acid, Action of sucrose with Nitric acid, Reaction of Ethanol and acid, Electrolytic method, Membrane separation method. Leaching studies on nuclear waste have been studied.³ Evaporation is a proven method for the treatment of liquid radioactive waste. This process also produces clean condensate and also considered as the best technique for waste which has high salt content.⁴ High level liquid wastes are first cycle raffinates it also includes fission products thus they should be stored in suitably designed tanks, but this method is safe under close surveillance.⁵ In this paper volume reduction of high-level nuclear waste was performed with the help of evaporation process performed in a Thermosyphon evaporator, the condensate, raffinates were analyzed for its acidity value. The equipment used for volume reduction was designed by using the design equations.⁶

EXPERIMENTAL

High-level radioactive liquid waste (raffinate) that has been generated from reprocessing plants is stored in raffinate feed storage tanks. This raffinate is concentrated by evaporation to reduce the required storage
The thermosyphon evaporator is fed continuously by an air lift pump at a designed flow rate 400 lph from raffinate feed storage tank. The flow rate is measured by rotameter and controlled by an automated operated valve. The liquid level in the evaporator is controlled by level indicating sensors which actuates feed control valve. The liquid waste is heated by steam to its boiling point by a steam tube bundle located within the evaporator. The steam supply is regulated by a flow control valve. The temperature in the evaporator is maintained about 378 K. The vapor which is generated in the evaporator contains liquid droplets that are contaminated with radioactive cesium and other trace radio nuclides. The vapor is passed through a high-efficiency demister pad to remove all liquids and thus removes the radioactive contaminants. The demister pad is located at the top of the evaporator. Overhead vapor is condensed in a shell and tube heat exchanger called Downdraft condenser and then collected in a low-level waste storage tank at a flow rate of 150 lph. This low-level condensate waste is discharged to the environment when its activity is below the permissible level. Noncondensable gases coming off the overhead condenser are passed through high-efficiency particulate (HEPA) filter and monitored for radioactivity before being vented to atmosphere. Waste concentrate called as high-level liquid waste is removed and stored in the high level liquid waste storage tank.

Corrosion and erosion are generally more severe problems in evaporators than any other types of equipment because of the necessary concentration differences, the frequent presence of solids in suspension and the high velocities of vapor and liquid.

Foaming is often a major problem because of the presence of soaps and detergents in varying concentrations. Even with trace levels of foaming agents, serious foaming occurs under vigorous boiling conditions in an evaporator and this leads to an operating flow rate considerably below the designed throughput. Evaporators depend entirely upon good heat transfer for their operation and scaling results in overall resistances to heat transfer increasing with time. The design of evaporators was performed to analyze important parameters with the help of material balance and energy balance. When the energy balance is calculated the load from vapor is calculated from the following equations:

\[ \text{Load from vapor (Q_v)} = m \lambda_v = q_v \times \rho \times \lambda_v \] (1)

\[ \text{Load from liquid (Q_L)} = q_f \times \rho \times (H_v - H_L) = (q + q_f) \times \rho \times (H_v - H_L) \] (2)

From Coulson and Richardson Vol-6 many important parameters were identified and the relations expressed in the above-said book is used to calculate these parameters. Total heat load was found by summing up the load from vapor and load from the liquid.

Heat transfer area required\(=\frac{Q}{U \times \Delta T} \) (3)

Flow area available is calculated by \(= \frac{\pi}{4} D_i^2 \times \text{no of tubes} \) (4)

The bundle diameter \(D_b = D_o \left( \frac{N_t}{K_1} \right)^{\frac{1}{n_1}} \) (5)

For triangular pitch \(K_1 = 0.319 \quad n_1 = 2.142, \quad N_t \) is total number of tubes and \(D_b = 33.528 \text{mm} \left( \frac{32}{0.319} \right)^{\frac{1}{2.142}} \)

Pressure drop inside the evaporator was calculated using the relation:

\[ \Delta P = 8 f_i \left( \frac{L}{D_j} \right) \left( \frac{\rho u^2}{2} \right) \] (6)

Static pressure inside the tubes is calculated using:

\[ \Delta P_s = -\frac{gL}{(v_0 - v_i)} \times \ln \left( \frac{v_0}{v_i} \right) \] (7)
In forced-convective boiling, the effective heat-transfer coefficient \( h_{cb} = h'_{fc} + h'_{nb} \). The convective boiling co-efficient is expressed by \( h'_{fc} = f_c \times h' \) and Nucleate boiling co-efficient \( h'_{nb} = h_{nb} \times f_s \). Overall Heat transfer Co-Efficient was calculated from the relation:

\[
\frac{1}{U_C} = \frac{1}{h_t D_t} + \frac{X_w}{K_m D_L h_o} + \frac{1}{h_o}
\]

\( (8) \)

Dirt co-efficient was calculated using:

\[
R_d = \frac{U_{cw} - U_D}{U_{cw}U_D}
\]

\( (9) \)

**RESULTS AND DISCUSSION**

**Design of Thermosyphon Evaporator**

**Assumption**
- The influence of fission products on physical properties is neglected.
- The properties of water are used for feed and concentrate.

**Vapor Chamber Design**

From IAEA Tech Rep Series 87 (1968), p-34, \( DF = 1.2 \times 10^{14} G^{-3.7} \) (for \( G = 145 \) and above)

For \( DF=1000 \), the \( G = \left( \frac{1000}{1.2 \times 10^{14}} \right)^{-3.7} = 987.13 \) kg/hr m².

As the vapor mass flow rate is 149.69 kg/hr, the cross-sectional area of vapor chamber \( A_v = 0.53 \) m² hence the diameter of vapor chamber \( \approx 493 \) mm.

As the vapor flux is high, the diameter of vapor chamber is increased to 700 mm to reduce the vapor flux below 400 kg/m² hr.

As per IAEA Tech Rep Series 87 (1968), p-33, experiments under normal boiling conditions (mass velocities below 400 kg/m² h) show that the height of drops above the liquid level does not become extremely great due to vapour velocity and the conclusion is reached that if the height of vapour space is about 0.6 to 1.1 m, it is improbable for the jetted drops to reach the vapour outlet directly. Hence vapor chamber height of 1.5m is recommended for the evaporator. A Demister is provided inside the vapor chamber to enable mist elimination.

**Steam Inlet Nozzle Size**

- Latent heat of steam \( = 2185.5 \) kJ/kg
- Specific volume of Steam \( = 0.749 \) m³/kg

Steam required \( = \frac{\text{heat load}}{\text{latent heat}} = \frac{462257.25 \text{kJ/hr}}{2185.5 \text{kJ/kg}} = 211.51 \text{Kg/hr} \)

Volume of steam required \( = 0.749 \times 211.51 = 158.42 \text{ m}^3/\text{hr}. \)

Assuming a velocity of 15 m/s, c/s area required = 0.003 m².

Diameter = 0.062m = 62mm

Hence 50 NB Sch 40 SS pipe can be used

**Steam Condensate Drain Nozzle Size**

- Specific volume of condensate \( = 1.0658 \times 10^{-3} \) m³/kg
- Condensate volume \( = 1.0658 \times 10^{-3} \times 211.51 \text{kg/hr} = 0.2254 \text{ m}^3/\text{hr}. \)

Assuming a velocity of 0.3 m/s, c/s area required is \( 2.08 \times 10^{-4} \) m²

Diameter = 0.0162 m = 16.2mm
Hence 15 NB Sch 40 SS pipe can be used.

**Feed and Outlet Nozzles**

Total liquid Feed is (Condensate + Concentrate) = 400 lph

Assumed Velocity is 0.3m/s

Area of flow will be $3.7 \times 10^{-4}$ m$^2$

Diameter is 21.4 mm

Hence 20 NB Sch 40 SS pipe can be used.

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**Table-1: Material balance for Thermosyphon evaporator**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Feed</th>
<th>Concentrate</th>
<th>Distillate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow Rate in lph</td>
<td>400</td>
<td>250</td>
<td>150</td>
</tr>
<tr>
<td>Density in kg/m$^3$</td>
<td>1230</td>
<td>1315</td>
<td>1080</td>
</tr>
<tr>
<td>Normality N</td>
<td>3.65</td>
<td>5.0</td>
<td>1.4</td>
</tr>
<tr>
<td>Weight percentage of HNO$_3$</td>
<td>23</td>
<td>31.5</td>
<td>8.82</td>
</tr>
<tr>
<td>Weight percentage of H$_2$O</td>
<td>77</td>
<td>68.5</td>
<td>91.18</td>
</tr>
<tr>
<td>$\beta_g$ activity Ci/l</td>
<td>70.04</td>
<td>709.81</td>
<td>700.4 x$10^{-6}$</td>
</tr>
</tbody>
</table>

**Table-2: Energy Balance for thermosyphon evaporator**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Flow Rate in lph</th>
<th>Temperature in K</th>
<th>Enthalpy in KJ/kg</th>
<th>Total Enthalpy in KJ/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed in</td>
<td>400</td>
<td>303</td>
<td>125.60</td>
<td>50240.0</td>
</tr>
<tr>
<td>Steam in</td>
<td>170.3</td>
<td>400</td>
<td>2714.40</td>
<td>462262.32</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>512502.32</td>
</tr>
<tr>
<td>Concentrate out</td>
<td>250</td>
<td>378</td>
<td>439.96</td>
<td>109990.0</td>
</tr>
<tr>
<td>Vapor out</td>
<td>150</td>
<td>378</td>
<td>2683.40</td>
<td>402510.0</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
<td>512500.0</td>
</tr>
</tbody>
</table>

**Table-3: Design Summary of Thermo Siphon Evaporator**

| Parameters             | Feed Rate, lph | Evaporator duty, lph | Concentrate Flow Rate, lph | Boiling point of solution, K | Frictional pressure drop, N/m$^2$ | Static pressure drop, N/m$^2$ | Total pressure drop, N/m$^2$ | Driving force, N/m$^2$ | Heat transfer coefficient,Uc W/m$^2$K | Heat transfer coefficient,Ud W/m$^2$K | Dirt factor,Rd m$^2$K/W | Heat transfer area provided, m$^2$ | Heat flux, W/m$^2$ | Shell diameter, mm | Shell thickness, mm | Tube sheet diameter, mm | Tube sheet thickness, mm | Number of tubes | Pipe diameter (NB), Sch 40, mm |
|------------------------|----------------|---------------------|---------------------------|-------------------------------|----------------------------------|-------------------------------|-------------------------------|-------------------------|-----------------------------|-----------------------------|-------------------------|----------------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
### DESIGN OF THERMOSPYPHON EVAPORATOR

<table>
<thead>
<tr>
<th>Tie rod Diameter , mm</th>
<th>9.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of tie rods</td>
<td>4</td>
</tr>
<tr>
<td>Vapour chamber dia , mm</td>
<td>700</td>
</tr>
<tr>
<td>Mass Flux in vapour chamber, Kg/hr-m²</td>
<td>400</td>
</tr>
<tr>
<td>Evaporator vent pipe (NB), Sch 40, mm</td>
<td>150</td>
</tr>
<tr>
<td>Velocity in vent pipe, m/s</td>
<td>15</td>
</tr>
<tr>
<td>Cold leg pipe diameter (NB), Sch 40, mm</td>
<td>150</td>
</tr>
<tr>
<td>Recirculation Ratio</td>
<td>250</td>
</tr>
<tr>
<td>Feed inlet &amp; outlet nozzle diameter (NB), Sch40, mm</td>
<td>20</td>
</tr>
<tr>
<td>Steam nozzle diameter (NB), Sch 40, mm</td>
<td>50</td>
</tr>
<tr>
<td>Condensate drain nozzle diameter (NB), Sch 40, mm</td>
<td>15</td>
</tr>
<tr>
<td>Baffle Clearance, mm</td>
<td>3.2</td>
</tr>
<tr>
<td>Baffle Diameter (Shell ID- 2x Baffle Clearance)</td>
<td>296.6</td>
</tr>
<tr>
<td>No of Baffles</td>
<td>8</td>
</tr>
<tr>
<td>Vapour Outlet Dia, mm</td>
<td>80</td>
</tr>
</tbody>
</table>

### CONCLUSION

Volume reduction method is good practice that is done to reduce the toxic liquid waste which is very tough to handle. Thus this study has revealed that evaporation process can result in volume reduction of nuclear waste and if it is performed by thermosyphon evaporator the result would be better. Thus a suitable evaporator column was designed to perform volume reduction.

### REFERENCES


[RJC-1964/2017]