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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

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volume. The thermosyphon evaporator is fed continuously by air lift pump at a designed flow rate 400 lph from rafiinate 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:

Load from vapor (Q_v) $= \dot{m}\lambda_{ev} = q_v \times \rho \times \lambda_{ev}$ (1)

Load from liquid (Q_P)= $q_f \times \rho \times (H_v - H_L) = (q + q_c) \times \rho_v \times (H_v - H_L)$ (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 $D_b = D_o \left(N_t / K_1 \right)^{1/n_1}$ (5)

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

Pressure drop inside the evaporator was calculated using the relation:

$$\Delta P = 8 j_f \left(\frac{L}{D_i} \right) \left(\frac{\rho u^2}{2} \right) \quad (6)$$

Static pressure inside the tubes is calculated using:

$$\Delta P_s = \frac{gL}{(v_0 - v_i)} \times \ln \left(\frac{v_0}{v_i} \right) \quad (7)$$

In forced-convective boiling, the effective heat-transfer coefficient $h_{cb} = h'_{fc} + h'_{nb}$, The convective boiling co-efficient is expressed by $h'_{fc} = h_{fc} \times f_c$ and Nucleate boiling co-efficient $h'_{nb} = h_{nb} \times f_s$ Overall Heat transfer Co-Efficient was calculated from the relation:

$$\frac{1}{U_C} = \frac{1}{h_i}\frac{D_o}{D_i} + \frac{X_W}{K_m}\frac{D_o}{D_L} + \frac{1}{h_o} \quad (8)$$

Dirt co-efficient was calculated using:

$$R_d = \frac{U_{Cw} - U_D}{U_{Cw} U_D} \quad (9)$$

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, $\mathrm{DF} = 1.2\times10^{14}\ \mathrm{G}^{-3.7}\ (\text{ for G} = 145 \text{ and above})$

For DF=1000, the $G = \left(\frac{1000}{1.2\times10^{14}}\right)^{\frac{1}{-3.7}}$ = 987.13 kg/hr m^2.

As the vapor mass flow rate is 149.69 kg/hr. the cross-sectional area of vapor chamber A_v= 0.53 m^2 hence the diameter of vapor chamber ≈ 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/m^2 hr.

As per IAEA Tech Rep Series 87 (1968), p-33, experiments under normal boiling conditions (mass velocities below 400 kg/m^2 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 m^3/kg
Steam required $= \frac{\text{heat load}}{\text{latent heat}} = \frac{462257.25\,\text{kJ/hr}}{2185.5\text{kJ/kg}}$
= 211.51Kg/hr
Volume of steam required = 0.749 ×211.51= 158.42 m^3/hr.
Assuming a velocity of 15 m/s, c/s area required = 0.003 m^2.
Diameter = 0.062m =62mm
Hence 50 NB Sch 40 SS pipe can be used

Steam Condensate Drain Nozzle Size

Specific volume of condensate = 1.0658x10^{-3} m^3/kg
Condensate volume = 1.0658x10^{-3} ×211.51kg/hr
= 0.2254 m^3/hr.
Assuming a velocity of 0.3 m/s, c/s area required is 2.08x10^{-4} m^2
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 $3.7X10^{-4}$ m^2
Diameter is 21.4 mm
Hence 20 NB Sch 40 SS pipe can be used

Table-1: Material balance for Thermosyphon evaporator

Parameters	Feed	Concentrate	Distillate
Flow Rate in lph	400	250	150
Density in kg/m^3	1230	1315	1080
Normality N	3.65	5.0	1.4
Weight percentage of HNO_3	23	31.5	8.82
Weight percentage of H_2O	77	68.5	91.18
β,g activity Ci/l	70.04	709.81	700.4×10^{-6}

Table-2: Energy Balance for thermosyphon evaporator

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

Table-3: Design Summary of Thermo Siphon Evaporator

Feed Rate, lph	400
Evaporator duty, lph	150
Concentrate Flow Rate, lph	250
Boiling point of solution, K	378
Frictional pressure drop, N/m^2	2023
Static pressure drop, N/m^2	7206
Total pressure drop, N/m^2	11253
Driving force, N/m^2	24175
Heat transfer coefficient,Uc W/m^2K	1891
Heat transfer coefficient,Ud W/m^2K	840
Dirt factor,Rd m^2K/W	0.004
Heat transfer area provided, m^2	7.181
Heat flux, W/m^2	17839
Shell diameter, mm	303
Shell thickness, mm	6
Tube sheet diameter, mm	288
Tube sheet thickness, mm	38
Number of tubes	29
Pipe diameter (NB), Sch 40, mm	25

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

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.

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