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Thermosiphon Reboiler Design and Analysis for Water Distillation Applications

Rupsha Bhattacharyya
Heavy Water Division, Bhabha Atomic Research Centre
Trombay, Mumbai, Maharashtra, India
Email: rupshabhattacharyya1986@gmail.com, rupsha@barc.gov.in

Abstract: Purification of heavy water used as the moderator and coolant of pressurized heavy water nuclear reactors (PHWRs) is a vital step in ensuring its adequate isotopic content that maintains neutron economy in the reactor core. This process is carried out in a packed vacuum distillation column which requires condensers and reboilers as essential heat transfer components. A vertical thermosiphon reboiler is used to minimize operating costs of the distillation system by eliminating the fluid recirculation pump and improving system reliability and safety by minimizing leakages and heavy water losses. This work presents a simple, direct methodology for optimizing the design and operation of such a reboiler using codes developed in-house and based on heuristics and two-phase heat and momentum transfer correlations from literature. The methodology is general and can be applied to any application requiring a thermosiphon reboiler. Parametric analysis and cost calculations have also been performed along with exergy analysis of reboiler performance.

Keywords: Optimization, Parametric analysis, Thermosiphon reboiler, Water distillation.

I. Introduction

Heavy water describes water in which the content of deuterium (H_1^2), present as D_2O and HDO, is higher than the natural proportion of about 150 parts per million (ppm) in light water. It is an isotopic form of water and therefore it is chemically similar to light water (H_2O), but the two species have slight differences in boiling point and other physical properties [1]. Heavy water is an integral part of nuclear power generation systems which use natural uranium (in the form of uranium oxide) as fuel because of its very good moderating power and extremely low neutron capture cross section. Moreover it is also used as the coolant to remove nuclear heat from the reactor core, which is then used to generate steam and subsequently electricity [2]. During normal operations the heavy water moderator and coolant get contaminated by light water from ambient air or from any sources of leakage through various mechanisms. This is detrimental to its moderating power as the presence of hydrogen i.e. in the form of light water seriously affects neutron economy in the reactor core. So both the moderator and coolant need to be purified to at least 99.9% deuterium [3, 4]. This is achieved by a process of vacuum distillation in packed columns containing high efficiency structured packing along with the ancillary heat exchangers like the reflux condensor and the reboiler. This work focuses on the design and analysis of the reboiler for water distillation applications in the nuclear power arena. A recirculating thermosiphon reboiler is considered in this study as a part of the water distillation system. The work presented here focuses on the development of a systematic design and analysis methodology for thermosiphon reboilers along with its parametric optimization and economic analysis.

The operation of thermosiphon or natural circulation reboilers represent a strong coupling of thermal and mechanical interactions in fluid flow. Thus the design procedure is more complex than that of heat exchangers with no phase change or heat exchangers where phase change is taking place in one or both streams but with forced circulation arrangements. Similar considerations are applicable to the very widely used long tube vertical evaporators for liquors in the chemical process industries as well. While highly sophisticated proprietary commercial software is available for design and optimization of such heat exchangers, they are expensive and may not always be freely available to all users. This provides the motivation to develop in-house codes for preliminary design and analysis work based on theoretical and empirical correlations and data in published literature. Since there is an enormous amount of literature available for modeling two phase flows particularly in condensation and vapourization applications, judicious selection of the design equations must be made to arrive at a reliable heat exchanger design. Some of the design guidelines for thermosiphon reboiler design available in literature and utilized in this work for a computationally less intensive design exercise are summarized in Table I:

Table I: Review of Literature on Design Guidelines for Thermosiphon Reboilers [5-11]

Serial No. [Ref.]	*Area of Focus*	*Major Findings*
1 [5]	Collecting and verifying a wide range of existing correlations and experimentally obtained data for calculation of two phase flow friction factors.	2 correlations based on separated flow model of two phase flows have been identified as the best (i.e. having highest accuracy and match with experimental results) for predicting pressure drops over a wide range of flow conditions and regimes.
2 [6]	Description of operational characteristics and effect of design and operational parameters of thermosiphon reboilers.	Thermosiphon reboilers have been envisaged as having two zones, one for heating and one for evaporation of the circulating fluid. This has been used to carry out parametric studies for design and operation of these reboilers.
3 [7]	Study of thermosiphon reboiler operation near the maximum allowable heat flux conditions	Equations for predicting allowable maximum heat flux in thermosiphon reboilers using vapour and liquid properties and tube geometries have been obtained for a wide range of reduced pressure conditions. These form the starting point for prediction of area requirements in a reboiler for a given service.
4 [8]	Development of a computer aided design methodology for thermosiphon reboilers.	Comprehensive collection of equations available in literature for thermal and hydrodynamic design of the reboilers has been collated in this work. Algorithms for performing these calculations in different flow regimes have been presented and calculations have been validated with results in literature.
5 [9]	Complete review of thermal and momentum transfer related correlations for various kinds of two phase flow, not limited to vapour-liquid flows alone.	Comprehensive collection of equations available in literature for various kinds of two-phase flows in various geometries have been presented here in a form very suitable for computer aided design.
6 [10]	Presentation of a simple but generalized correlation for saturated flow boiling in horizontal and vertical tubes.	The generalized explicit correlation, which requires thermal design data and thermophysical fluid properties, has been validated using more than 5000 experimental data points covering 10 different kinds of fluids, both aqueous and non-aqueous. This is a marked refinement of an earlier work carried out by the same author.
7 [11]	Presentation of a generalized correlation for flow boiling in tubes and annular spaces.	A databank of 4300 experimental points pertaining to flow boiling of water, refrigerants and ethylene glycol has been used to derive a correlation that provides better predictions of saturated and sub-cooled flow boiling inside tubes and annuli. The deviation between the predictions from the correlation and the experimental points has a maximum value of 21-25%.

II. Physical Property Data for Water Distillation System

The process streams as well as the hot and cold utilities considered here are all based on water in vapour (i.e. steam) or liquid form. Thus a consistent set of data pertaining to the physical properties of these streams were used. Physical property data from literature [12] for saturated liquid water and for saturated water vapour were fitted to polynomial regression functions. These equations were used in all the design and optimization calculations. Equations (1) to (5) are for liquid water properties while equations (6) to (9) are for water vapour or steam properties. Entropy of vapourization/condensation of water was estimated from Equation (10). Temperature dependent enthalpy of vapourization/condensation data for water was estimated from the Riedel and Watson correlations, shown in Equations (11) and (12) [13]. Here the slight differences in the physical properties of light and heavy water were ignored (except for critical properties and vapour pressure data) since these minor variations are unlikely to have any significant impact on the subsequent exergy calculations and optimization.

$$v_l = -2.2911 * 10^{-12} t^4 + 6.6474 * 10^{-10} t^3 - 7.9237 * 10^{-8} t^2 + 4.1465 * 10^{-6} t + 9.4626 * 10^{-4} \quad (1)$$

$$C_{pl} = 4.4513 - 2.6893 * 10^{-2} t + 7.713 * 10^{-4} t^2 - 9.3379 * 10^{-6} t^3 + 5.4717 * 10^{-8} t^4 - 1.5196 * 10^{-10} t^5 + 1.6198 * 10^{-13} t^6 \quad (2)$$

$$\sigma = \frac{77.09 - 0.179t - 9 * 10^{-5} t^2}{1000} \quad (3)$$

$$\mu_l = 0.017998 t^{-0.927} \quad (4)$$

$$k_l = 0.5722 + 1.6775 * 10^{-3} t - 5.9952 * 10^{-6} t^2 \quad (5)$$

$$v_g = 4.16 * 10^{-12} t^6 - 5.335 * 10^{-9} t^5 + 2.702 * 10^{-6} t^4 - 6.856 * 10^{-4} t^3 + 9.1 * 10^{-2} t^2 - 5.954t + 151.3 \quad (6)$$

$$C_{pg} = 4.777 * 10^{-9} t^4 - 2.5725 * 10^{-6} t^3 + 4.9065 * 10^{-4} t^2 - 3.1186 * 10^{-2} t + 2.3761 \quad (7)$$

$$\mu_g = \frac{6.1 * 10^{-9} t^4 - 3.8 * 10^{-6} t^3 + 7.5 * 10^{-4} t^2 - 1.29 * 10^{-2} t + 9.02}{10^6} \quad (8)$$

$$k_g = 6.6314 * 10^{-4} t^4 - 3.9053 * 10^{-2} t^3 + 0.7844 t^2 - 4.8117 t + 26.885 \quad (9)$$

$$s_{fg} = 9.061 - 3.604 * 10^{-2} t + 5.847 * 10^{-5} t^2 \quad (10)$$

$$\Delta h_{vn} = \frac{1.093 R_g T_c \left[T_{br} \frac{\ln P_c - 1.013}{0.93 - T_{br}} \right]}{18} \quad (11)$$

$$h_{fg} = \Delta h_{vn} \left[\frac{1 - T_r}{1 - T_{br}} \right]^{0.38} \quad (12)$$

The value of standard state enthalpy of formation of water was taken as -285 kJ mol^{-1} and standard state entropy of formation of water was taken as 70 J mol^{-1} K^{-1} [14].

III. Model Equations for Thermosiphon Reboiler Sizing

A. Design Algorithm

The sequence of steps in sizing the thermosiphon reboiler was as shown in Table II [15-17]:

Table II: Thermosiphon Reboiler Design Algorithm

Step No.	*Calculation*
1	Calculation of heat duty based on circulation ratio and feed flow rate.
2	Calculation of hot utility/steam requirement through energy balance.
3	Assumption of maximum allowable heat flux in the reboiler.
4	Calculation of heat transfer area required based on heat flux and heat duty.
5	Assumption of tube length, tube diameter and calculation of number of tubes.
6	Calculation of total tube side pressure drop, considering two-phase boiling flow, for maintaining chosen circulation ratio in the tubes.
7	Calculation of available pressure driving force in the cold leg of the column for single phase (liquid) conditions.
8	If value in Step 6 is lesser than value in Step 7, then design is adequate from hydraulic point of view. If not, go to step 1 and revise circulation ratio (not less than 3.0) and step 5 to revise reboiler tube length.
9	Calculation of boiling heat transfer coefficient inside tubes.
10	Calculation of condensing heat transfer coefficient outside tubes.
11	Calculation of overall heat transfer coefficient available by design while allowing for suitable fouling factors on both sides.
12	If value in Step 11 is greater than value of overall heat transfer coefficient calculated in Step 4 by about 20-25%, thermal design of reboiler is adequate for given heat duty.
13	If value in Step 11 is lesser than value of overall heat transfer coefficient calculated in Step 4 thermal design of reboiler is inadequate for given heat duty; go to step 5 to revise tube length and Step 1 to revise circulation ratio.
14	Calculation of shell side diameter, pressure drop.
15	Calculation of exchanger cost (based on weight of material of construction and fabrication expenses) and exergetic efficiency based on process/operating and ambient conditions.

The calculation of heat transfer coefficients and pressure drops for the shell side and tube side fluids are described in the following subsections. The calculations were first performed for the base case conditions described in Table III and parametric analysis was carried out next.

B. Design Equations for Tube Side

The boiling heat transfer coefficient inside the tubes of the reboiler was obtained by the following sequence of calculations [15]:

$$h_{total} = F_{Chen} h_c + Sup_{Chen} h_{boiling} \quad (13)$$

$$X_{tt} = \left(\frac{\rho_l}{\rho_v} \right)^{0.5} \left(\frac{\mu_v}{\mu_l} \right)^{0.1} \left(\frac{1 - x}{x} \right)^{0.9} \quad (14)$$

$$F_{Chen} = \max[2.35 (X_{tt}^{-1} + 0.213)^{0.736}, 1] \quad (15)$$

$$Re_{Chen} = 10^{-4} F_{Chen}^{1.25} (1 - x) \frac{G D_h}{\mu_l} \quad (16)$$

$$Sup_{Chen} = (1 + 0.12Re_{Chen}^{1.14})^{-1}, for\ Re_{Chen} < 32.5 \tag{17}$$

$$Sup_{Chen} = (1 + 0.42Re_{Chen}^{0.78})^{-1}, for\ 32.5 < Re_{Chen} < 70 \tag{18}$$

$$Sup_{Chen} = 0.0797 \exp\left(1 - \frac{Re_{Chen}}{70}\right), for\ 70 \geq Re_{Chen} \tag{19}$$

Forced convective heat transfer coefficient for single phase liquid flow in the reboiler tubes was expressed as [15]

$$\frac{h_c D_h}{k_l} = 0.023 Re_l^{0.8} Pr_l^{0.4} \tag{20}$$

The nucleate boiling coefficient was expressed as [15]

$$h_{boiling} = 0.104 (P_c)^{0.69} q^{0.7} \left[1.8\left(\frac{P}{P_c}\right)^{0.17} + 4\left(\frac{P}{P_c}\right)^{1.2} + 10\left(\frac{P}{P_c}\right)^{10}\right] \tag{21}$$

Pressure drop for two-phase flow inside the tubes consists of the following terms [12]:

$$\Delta P_{tube} = \Delta P_{friction} + \Delta P_{local} + \Delta P_{elevation} + \Delta P_{accln} \tag{22}$$

Each of the terms was calculated as described in the next few paragraphs.

Owing to changing fluid quality inside the reboiler tubes as the liquid is progressively vapourized, there is changing density and changing velocity inside tubes. This gives rise to an acceleration related pressure losses which was accounted for by the following equation [12]:

$$\Delta P_{accln} = m_{tube}^2 \left\{\left[\frac{(1-x)^2}{\rho_l(1-\epsilon)} + \frac{x^2}{\rho_g \epsilon}\right]_{outlet} - \left[\frac{(1-x)^2}{\rho_l(1-\epsilon)} + \tag{23}\right.\right.$$

$$\left.\left.\frac{x^2}{\rho_g \epsilon}\right]_{inlet}\right\} \tag{24}$$

Depending on the tube length there is an elevation head to be overcome which was calculated as

$$\Delta P_{elevation} = \rho_m g L \tag{25}$$

Elevation in boiling point of tube side fluid due to liquid head at reboiler inlet was not considered in the heat transfer calculations, though this factor will tend to reduce the available heat transfer temperature driving force and lead to enhanced heat transfer area requirement.

For liquid only flowing in the tubes, the pressure drop per unit tube length due to friction losses + tube entry loss + tube exit loss was evaluated by

$$\left(\frac{dP}{dz}\right)_{liq} = 0.5 * \frac{(\alpha \rho_l V_l)^2}{\rho_l} \frac{f_l}{D_h} + 2 * 0.5 * \frac{(\alpha \rho_l V_l)^2}{\rho_l} \frac{\xi_{loss}}{\Delta z} \tag{26}$$

The friction factor for turbulent single phase liquid flow in a rough reboiler tube was found from the following explicit relationship [18]

$$f_l = \frac{0.33125}{\left[\ln\left(\frac{e}{3.7D} + \frac{5.74}{Re_l^{0.9}}\right)\right]^2} \tag{27}$$

For two phase flow in the same tube, the frictional pressure drop in terms of the single liquid phase pressure drop was ultimately expressed by [15]

$$\left(\frac{dP}{dz}\right)_{TP} = \Phi_L^2 \left(\frac{dP}{dz}\right)_{liq} \tag{28}$$

Where

$$\Phi_L^2 = 1 + \frac{20}{X_{tt}} + \frac{1}{X_{tt}^2} \tag{29}$$

Thus

$$\Delta P_{friction} + \Delta P_{local} = L * \left(\frac{dP}{dz}\right)_{TP} \tag{30}$$

The average frictional pressure drop in the tubes is taken as the arithmetic mean of the pressure drop based only on inlet single phase conditions and pressure drop based only on outlet two phase conditions.

C. Design Equations for Shell Side

The steam condensation coefficient on the shell side i.e. outside the vertical tubes of the reboiler was calculated from the Nusselt model as follows [15, 16]:

$$h_{steam} = 0.926 k_l \left[\frac{\rho_l(\rho_l - \rho_v) g}{\mu_l \Gamma_v}\right]^{\frac{1}{3}} \tag{31}$$

$$\Gamma_v = \frac{W_c}{N_t \pi d_o} \tag{32}$$

The shell side pressure drop for the condensing steam flow was obtained as follows [16]:

$$\Delta P_{shell} = \frac{f_s G_{steam}^2 D_{shell}(N_b + 1)}{2g \rho_{steam} D_H} \tag{33}$$

$$Re_{shell} = \frac{D_H G_{steam}}{\mu_{steam}} \tag{34}$$

$$D_H = \frac{4\left(pt^2 - \frac{\pi d_o^2}{4}\right)}{\pi d_o} \tag{35}$$

$$G_{steam} = \frac{W_c}{a_{shell}} \tag{36}$$

$$a_{shell} = \frac{c' B D_{shell}}{pt} \tag{37}$$

Condensing steam properties were all evaluated at the mean film temperature which was taken as the arithmetic mean temperature of the shell and tube side fluids. For pressure drop calculations on the shell side, properties of dry saturated steam and not the two phase mixture on shell side were used everywhere.

The overall heat transfer coefficient for the reboiler was calculated as [15]

$$\frac{1}{U_o} = \frac{1}{h_{steam}} + \frac{1}{h_{OD}} + \frac{d_o \ln\frac{d_o}{d_i}}{2k_w} + \frac{d_o}{d_i h_{ID}} + \frac{d_o}{d_i h_{total}} \tag{38}$$

Fouling factors were taken as 6000 W/m^2 K for tube side process fluid and 5000 W/m^2 K for the shell side condensing steam. For a given heat duty as determined from the vapourization rate, the area was evaluated as:

$$Q = U_o A_o \Delta T_{LMTD} = m_{steam} h_{fgsteam} = m_{tube} (h_l + h_{fgtube} x) \tag{39}$$

In this work the available heat transfer coefficient based on the tentatively chosen design data was compared to the required overall heat transfer coefficient based on the recommended maximum allowable heat flux value for thermosiphon reboilers in aqueous service.

TABLE III: BASE CASE DATA FOR THERMOSIPHON REBOILER DESIGN

Variable/Parameter	*Value*
Vapour flow rate required at reboiler outlet	150 kg/hr
Liquid to vapour circulation rate	4.5:1
Feed liquid flow rate at reboiler inlet	675 kg/hr
Column bottom pressure	0.3 bar (a)
Bubble point of liquid at column bottom pressure	72 °C
Material of construction of shell and tubes	SS 304L
Tube dimensions (length/inside diameter/ outside diameter)	1.5 m / 20 mm / 25 mm
Tube roughness element height	0.04 mm
Heating steam temperature/pressure on shell side	120 °C / 8 bar (a)
Ambient temperature	30 °C
Cost of SS 316 sheets and tubes for reboiler fabrication	Rs. 500 / kg [19]
Reboiler availability factor	80% per annum
Reboiler life	10 yr
Tube wall thermal conductivity	16 W/m K [22]

D. Exergy Analysis

The transfer of heat from the hot utility to the cold process stream takes place across a finite temperature difference driving force, thereby making the heat transfer process an irreversible one. Moreover there are frictional pressure losses on both sides as the fluids flow through the reboiler [20, 21]. All these irreversibilities contribute to exergy destruction or lost work during heat exchanger operation. In this section, the extent of irreversibility and the thermodynamic second law efficiency or exergetic efficiency of the reboiler are examined. For the reboiler, there is heat transfer with phase change in both shell side and tube side fluid but the heat transfer on either side is isothermal. Thus the calculation of enthalpy and entropy changes for each fluid simply involves gain or loss of latent heat of vapourization/condensation and entropy change in vapourization/condensation, at the appropriate temperature and pressure levels. Along with these terms, lost work due to total pressure drop in each stream was also accounted for by considering the total work equivalent of the pressure loss. Hence the exergy change of each stream was expressed as follows:

$$\psi_{tubeout} - \psi_{tubein} = m_{tube} [(h_{tubeout} - h_{tubein}) - T_o (s_{tubeout} - s_{tubein}) - \rho_m \Delta P_{tube}] \tag{40}$$

$$\psi_{shellout} - \psi_{shellin} = m_{shell} [(h_{shellout} - h_{shellin}) - T_o (s_{shellout} - s_{shellin}) - \rho_{steam} \Delta P_{shell}] \tag{41}$$

The exergetic efficiency of the reboiler is therefore expressed by the following equation [20]:

$$\eta_{exergy} = 100 * \frac{(\psi_{tubeout} - \psi_{tubein}) m_{tube}}{(\psi_{shellout} - \psi_{shellin}) m_{shell}} \tag{42}$$

The significance of exergy analysis is that it helps in the identification of conditions that make the reboiler operation approach reversible conditions more closely. Higher the efficiency, greater is the approach to reversibility.

E. Economic Analysis

The selection of a particular heat exchanger and its operating conditions is ultimately based on economic considerations. Thus preliminary cost estimates of the exchanger are also made using the current material cost and fabrication costs of the shell and tube, operating cost for utility steam and assuming straight line depreciation over the equipment lifetime of 10 years.As there is no forced circulation using a pump there is no consideration of the pump cost or the pumping cost in this model. The fixed cost of the reboiler is:

$$C_{reboiler} = (W_t + W_{shell}) * C_{steel} * F_f \tag{43}$$

The fabrication factor is taken as 2.0. The levelised cost per unit feed liquid processed in the reboiler (assuming 80% availability factor per annum for 10 years) is calculated as:

$$LC_r = \frac{C_{reboiler} + m_{shell} * 10 * .8 * 86400 * 365}{m_{tube} * 10 * .8 * 86400 * 365} \tag{44}$$

The above cost does not include the additional cost required to raise the water distillation column support structure to increase the liquid level head available for liquid recirculation at the desired rate.

IV. PARAMETRIC STUDIES AND RESULTS

A. Results for Base Case Operating Data

The basic reboiler design parameters calculated using the algorithm in Table II for the base case operating conditions in Table III are shown in Table IV.

TABLE IV: CALCULATED DESIGN DATA FOR BASE CASE THERMOSIPHON REBOILER

Variable/Parameter	*Value*
Number of tubes	39
Shell diameter (m)	0.29
Total area (m^2)	3.65

Tube pitch (m)	0.0313
Steam flow rate required (kg/s)	0.063
Tube side total pressure drop (Pa)	3857
Tube side available pressure differential (Pa)	14374
Overall heat transfer coefficient required (W/m^2 K)	789.6
Overall heat transfer coefficient available by design (W/m^2 K)	1114.8
Shell side pressure drop (Pa)	21.8
Second law/exergy efficiency of the reboiler (%)	5.862
Reboiler cost (Rs)	135395
Levelised cost of feed processing (Rs/kg feed liquid)	0.21

The design was found to have adequate pressure drop margin and heat transfer area margin for the given duty and was therefore deemed acceptable. The same methodology can be followed for the design of other systems employing a thermosiphon reboiler.

B. Parametric Sensitivity Analysis

Design and operating parameters of the base case reboiler were varied and the effect of these changes on the sizing, costing and efficiency of the reboiler are examined in this section. Some of the operating parameters in Table III were varied by ±10% from the base case values in turn while keeping the other values constant and the changes in reboiler design data in Table IV were examined. Trial and error calculations were performed for every change in parameter in order to ensure that the required circulation ratio and heat transfer area were ensured in the design in each case. The results are presented in Table V.

Table V: Sensitivity Analysis of Thermosiphon Reboiler Design and Operating Parameters

Parameter	*Variation*	*Design Data*					
		Number of Tubes	*Shell Diameter (m)*	*Tube Side Pressure Drop Margin*	*Overall Heat Transfer Coefficient Margin*	*Second Law Efficiency (%)*	*Levelised Feed Processing Cost (Rs/kg)*
Circulation ratio	+10%	39	0.29	3.445	1.415	6.478	0.19
	-10%	39	0.29	4.057	1.406	5.220	0.23
Tube length	+10%	36	0.28	3.232	1.419	5.944	0.21
	-10%	44	0.30	4.631	1.399	5.736	0.21
Steam temperature	+10%	39	0.29	3.726	1.762	5.756	0.21
	-10%	39	0.29	3.726	1.059	5.965	0.21
Tube inside diameter	+10%	36	0.28	4.986	1.427	3.676	0.21
	-10%	44	0.30	2.863	1.39	9.711	0.21

Increasing the circulation ratio increases pressure drop but also increases the heat transfer coefficients. The net effect in this case is a reduction in the heat transfer area and hence less expensive heat exchanger. Decreasing circulation ratio has precisely the opposite effect, leading to increased cost and lower exergetic efficiency of the reboiler. Increasing tube length increases available pressure head for a given circulation ratio but also increases pressure drop, thus the margin available goes down. But there is also an accompanying enhancement of the heat transfer area. The overall effect is a slight increase in efficiency but with no impact on the cost of the reboiler. Increasing steam temperature affects only the heat transfer area requirement by changing both the temperature driving force for heat transfer as well as the steam flow rate, because the latent heat of condensation is dependent on the temperature. Impact on exergetic efficiency and cost is seen to be negligible. Increasing the tube inside diameter while keeping the outer diameter constant decreases pressure drop on the tube side along with a decrease in the number of tubes required because of the overall increase in the heat transfer area. This leads to increased per tube velocity and higher overall heat transfer coefficient. But this reduces the exergetic efficiency significantly. The opposite situation is observed when decreased tube diameter is considered. Cost is not affected in either case. Based on the above analysis it can be suggested that a 10% increase in circulation rate through the reboiler tubes will allow the levelised processing cost to decrease by 10%, while maintaining adequate pressure drop (>300%) and heat transfer (>40%) margin for the given service. Thus circulation rate is by far the most important parameter for optimizing the design of the reboiler from an economic point of view.

V. Summary and Conclusion

A simple, direct method for thermosiphon reboiler design and analysis (including cost and second law thermodynamic analyses) has been demonstrated in this work. The case study considered for this purpose is that of a vertical thermosiphon reboiler for water distillation application as applicable to current pressurized heavy water nuclear reactor systems in India. The complete set of equations for rapidly sizing a reboiler through iterative means has been presented. The iterations pertain to selection of parameters like tube diameter, circulation ratio and tube lengths but the calculations of pressure drop and heat transfer parameters are non-iterative for a fixed set of values of the parameters. This precludes the use of graphs or tables in literature that are not convenient for using alongside computer calculations through spreadsheets or in-house codes.

A combination of the Lockhardt-Martinelli and Chisholm methods has been used for calculation of two phase pressure drop inside the reboiler tubes. Chen's method has been used for calculating the two phase heat transfer coefficient inside the reboiler tubes. A base case set of parameters has been assumed for the first design calculation, followed by an evaluation of the effect of variation of these parameters on the cost and efficiency of the reboiler. For the particular case study considered here the levelised cost of feed liquid processing varies between Rs 0.19 / kg to Rs 0.23 / kg liquid. The second law efficiency ranges from 3.7% to 9.7%, which is rather low for a shell and tube exchanger. The area requirement for the base case service is about 4 m^2. The design and analysis methodology proposed here is equally well applicable to the rapid sizing and costing of steam heated vertical evaporators for concentrating solutions. The accuracy of the calculations depends on the inherent accuracy of the empirical correlations used in the calculations.

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CONFLICT OF INTEREST

The author declares no conflict of interest.

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NOMENCLATURE

a_{shell}	Area for cross flow of fluid in shell side, m^2
c'	Spacing between two tubes, m
C_{pl}	Specific heat capacity of saturated liquid, kJ kg^{-1} K^{-1}
C_{pg}	Specific heat capacity of saturated vapour, kJ kg^{-1} K^{-1}
$C_{reboiler}$	Cost of reboiler, Rs
C_{steel}	Cost of stainless steel per kg, Rs/kg
D_h	Tube inside diameter, m
d_i	Inside diameter of tube, m
d_o	Outside diameter of tube, m
D_H	Hydraulic diameter of shell side, m
D_{shell}	Shell diameter, m
$(dP/dz)_{TP}$	Two phase pressure drop per unit length of reboiler tube, Pa m^{-1}
$(dP/dz)_l$	Liquid phase pressure drop per unit length of reboiler tube, Pa m^{-1}
e	Roughness element dimension, m
Ex	Specific exergy flow rate of any stream, kJ kg^{-1}
Ex_{RB1}	Exergy destruction rate in reboiler, W
f_l	Friction factor for liquid flow inside tubes, dimensionless
f_s	Friction factor for shell side fluid, dimensionless
F_{Chen}	Chen multiplier, dimensionless
F_f	Cost factor for fabrication, dimensionless
g	Acceleration dues to gravity, 9.81 m s^{-2}
G_{steam}	Mass velocity of steam on shell side, kg m^{-2} s^{-1}
h	Specific enthalpy of any stream, kJ kg^{-1}
$h_{boiling}$	Heat transfer coefficient for nucleate boiling inside tubes, W m^{-2} K^{-1}
h_c	Convective heat transfer coefficient for single phase flow, W m^{-2} K^{-1}
h_{fg}	Enthalpy change of vapourization/condensation of shell side or tube side fluid based on subscript, kJ kg^{-1}
h_l	Enthalpy of saturated liquid at reboiler tube side inlet, kJ kg^{-1}
h_{ID}	Dirt factor inside tubes, W m^{-2} K^{-1}
h_{OD}	Dirt factor outside tubes, W m^{-2} K^{-1}
h_o	Specific enthalpy of any stream at the dead state, kJ kg^{-1}
h_{total}	Total heat transfer coefficient inside tubes of reboiler, W m^{-2} K^{-1}
h_{steam}	Steam condensation coefficient, W m^{-2} K^{-1}
h	Specific enthalpy of any stream (as identified by its subscript), kJ kg^{-1}
k_l	Thermal conductivity of liquid, W m^{-1} K^{-1}
k_g	Thermal conductivity of vapour, W m^{-1} K^{-1}
k_w	Thermal conductivity of tube wall material, W m^{-1} K^{-1}
m_{shell}	Mass flow rate of shell side fluid, kg/s
m_{tube}	Mass flow rate of tube side fluid, kg/s
N_b	Number of baffles, dimensionless
N_t	Number of tubes in reboiler, dimensionless
pt	Tube pitch, m
P	Pressure of any stream, Pa
P_c	Critical pressure of water, bar

Pr_l	Liquid phase Prandtl number inside tubes, dimensionless
Q_R	Reboiler heat duty, W
q	Heat flux based on tube side area, W m^{-2}
Re_{Chen}	Reynolds number for two phase flow, dimensionless
Re_l	Reynolds number in tubes based on single phase flow, dimensionless
R_g	Universal gas constant, kJ $kmol^{-1}$ K^{-1}
s	Specific entropy of any stream (as identified by its subscript), kJ kg^{-1} K^{-1}
s_{fg}	Entropy change of vapourization/condensation, kJ kg^{-1} K^{-1}
s_o	Specific entropy of any stream at dead state, kJ kg^{-1} K^{-1}
Sup_{Chen}	Nucleate boiling suppression factor, dimensionless
t	Temperature, deg C
T	Absolute temperature, K
T_{br}	Reduced normal boiling point of water, dimensionless
T_c	Critical temperature of water, K
T_o	Ambient temperature, K
T_r	Reduced temperature of any stream, dimensionless
T_{steam}	Steam temperature for reboiler, K
U_O	Overall heat transfer coefficient in the reboiler, W m^{-2} K^{-1}
W_C	Steam condensate flow rate on the shell side, kg m^{-1} s^{-1}
W_{shell}	Weight of empty shell, kg
W_t	Weight of empty tubes, kg
x	Quality of flowing two phase stream in the reboiler tubes, dimensionless
X_{tt}	Lockhardt-Martinelli parameter, dimensionless
z	Tube length, m
α	Fraction of vapour in a given stream, dimensionless
Δh_{vn}	Enthalpy of vapourization at normal boiling point, kJ kg^{-1}
ΔP_{accln}	Pressure drop due to fluid acceleration, Pa
$\Delta P_{elevation}$	Pressure drop due to fluid elevation, Pa
$\Delta P_{friction}$	Pressure drop due to fluid friction in two phase flow, Pa
ΔP_{local}	Pressure drop due to local expansion and contraction losses, Pa
ΔP_{shell}	Pressure drop on shell side, Pa
ΔP_{tube}	Total pressure drop on tube side, Pa
ε	Volume void fraction in two phase stream, dimensionless
ξ	Local pressure loss coefficient, dimensionless
Γ_v	Steam condensate flow rate per unit length on the shell side, kg m^{-1} s^{-1}
η_{exergy}	Exergetic efficiency of reboiler, dimensionless
v_l	Specific volume of liquid stream, m^3 kg^{-1}
v_g	Specific volume of vapour stream, m^3 kg^{-1}
μ_l	Viscosity of liquid water, Pa s
μ_g	Viscosity of water vapour, Pa s
ρ_l	Liquid density, kg m^{-3}
ρ_m	Mean fluid density of two phase flow, kg m^{-3}
ρ_{steam}	Saturated steam density, kg m^{-3}
ρ_v	Vapour density, kg m^{-3}
Φ_L^2	Chisholm parameter, dimensionless
σ	Surface tension of water, N m^{-1}
ψ	specific exergy of any stream (as identified by subscript), kJ kg^{-1}

References

[1] M. G. Hawes, "Preparation of heavy water by catalytic exchange," *Platinum Metals Rev*., vol. 3, no. 4, pp. 118-124, 1959.

[2] S. Glasstone, and A. Sesonske, "Nuclear reactor engineering," *Reactor Design Basics,* vol. 1, 4th ed. CBS Publishers and Distributors, New Delhi, India, 2004.

[3] A. I. Miller, D. A. Spagnolo, and J. R. DeVore, "Choice of a process design for simultaneous detritiation and upgrading of heavy water for the advanced neutron source," *Nucl. Tech.,* vol. 112, no. 2, pp. 204-213, 1995.

[4] D. A. Spagnolo, and A. I. Miller, "The CECE alternative for upgrading/detritiation in heavy water nuclear reactors and for tritium recovery in fusion reactors," *Fus. Sci. Tech.* vol. 28, no. 3, pp. 748-754, 1995.

[5] Y. Xu, X. Fang, X. Su, Z. Zhou, and W. Chen, "Evaluation of frictional pressure drop correlations for two-phase flow in pipes," *Nuclear Engineering and Design*, vol. 253, pp. 86-97, 2012.

[6] S. Arneth, and J. Stichlmair, "Characteristics of thermosiphon reboilers," *Internal Journal of Thermal Science*, vol. 40, pp. 385-391, 2001.

[7] I. A. Furzer, "Vertical thermosiphon reboilers, maximum heat flux and separation efficiency," *Industrial and Engineering Chemistry Research*, vol. 29, pp. 1396-1404, 1990.

[8] N. V. L. S. Sarma, P. J. Reddy, and P. S. Murthi, “A computer design method for vertical thermosyphon reboilers,” *Industrial and Engineering Chemistry Process Design and Development,* vol. 12, no. 3, pp. 278-290, 1973.

[9] N. I. Kolev, *Multiphase Flow Dynamics*, vol. 4, 1st ed., Springer, Germany, 2006.

[10] S. G. Kandlikar, “A general correlation for saturated two-phase flow boiling heat transfer inside horizontal and vertical tubes,” *Journal of Heat Transfer*, vol. 112, pp. 219-228, 1990.

[11] K. E. Gungor, and R. H. S. Winterton, “A general correlation for flow boiling in tubes and annuli,” *International Journal of Heat and Mass Transfer,* vol. 29, no. 3, pp. 351-358, 1986.

[12] J. G. Collier, and J. R. Thome, *Convetive Boiling and Condensation,* 3rd ed., Oxford Science Publications, 2001.

[13] Y. V. C. Rao, *Chemical Engineering Thermodynamics*, Universities Press, India, 1997.

[14] Water: Condensed Phase Thermochemistry Data. [Online]. Available: https://webbook.nist.gov/cgi/cbook.cgi?ID=C7732185&Mask=2#Thermo-Condensed (last accessed 27.07.2018).

[15] G. Towler, R. Sinnott, “Chemical engineering design: Principles,” *Practice and Economics of Plant and Process Design*, Elsevier Inc., UK, 2008.

[16] D. Q. Kern, *Process Heat Transfer*, Tata McGraw Hill, 1950.

[17] S. B. Thakore, and B. I. Bhatt, *Introduction to Process Engineering and Design*, 1st ed., Tata McGraw Hill Publishing Company, New Delhi, 2007.

[18] A. K. Jain, *Fluid Mechanics Including Hydraulic Machines*, 2nd ed., New Delhi: Khanna Publishers, 2004.

[19] Stainless Steel 316L Price per Kg in India-Update 1. [Online]. Available: https://www.steelplates.in/stainless-steel-316l-price-per-kg-in-india-update-1/ (last accessed 27.07.2018).

[20] R. E. Sonntag, C. Borgnakke, and G. J. Van Wylen, *Fundamentals of Thermodynamics*, 6th ed., John Wiley and Sons Inc., New Delhi, 2005.

[21] T. J. Kotas, *The Exergy Method of Thermal Plant Analysis*, 1st ed., Krieger Publishing Company, 1995.

[22] Stainless Steel - Grade 316 (UNS S31600). [Online]. Available: https://www.azom.com/properties.aspx?ArticleID=863 (last accessed on 30.07.2018).