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Optimized copper alloy tubing configuration for a multi-stage flash distiller

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ABSTRACT

Copper alloys have successfully served as heat exchanger tubing material in multi-stage flash (MSF) desalination plants over decades. They showed, in general, good performance and are still designers' first choice. The big drawback of these high-alloyed stainless steel materials, however, is the lack of experience that has been made with as a tubing material in thermal desalination so far. The present work describes the experiences and observations made for cupronickel and aluminum brass tubes in three different MSF evaporators located at the Persian Gulf during an operational period of more than three decades. Results of eddy current tests accomplished in the course of refurbishment works are used to determine losses in tube wall thickness after the operation period. Based on the findings obtained an economically optimized tube configuration both in terms of material selection and wall thickness requirements is determined for an exemplary MSF desalination plant with a planned lifetime of thirty years. ASME VIII, Division 1, 2001 is drawn on for calculating the minimum required wall thickness of the different distiller stages. The corrosion allowance necessary for a tubing configuration not sustaining significant damages during this lifetime was calculated using corrosion rates got from eddy current test results and taking into account a tube failure rate of not more than 6% per stage. Detailed results are presented for the most significant stages. Stages were deemed to be most significant whenever a change in wall thickness or material selection became necessary to allow for the most economically efficient tubing configuration. The economical evaluation given is based on current material prices.

Keywords: Multistage flash (MSF); Material; Tubing; Copper; Economy; Optimization; Corrosion

1. Introduction

Driven by large investments in industries of emerging countries like Russia, India and China raw materials became scarce in the past. This want of raw materials tremendously affected the seawater desalination industry. Particularly, prices for copper and nickel rose dramatically. Copper for instance reached the fourfold in the past years of the price in 2000.

Current price developments on the raw material market show, after a significant release caused by diminishing investments due to the credit crunch, almost the same picture again. Hence, it is of utmost importance to search for the most economical material configuration for desalination plants in order to facilitate further investments in future desalination projects.

The industry is forced to be on the look out for alternatives. However, the big drawback of all these alternatives is their lack of experience that has been made with so far. Large desalination projects with planned lifetimes of twenty years and more require reasonable assessment of possible corrosion risks, materials losses and failures, which in fact is challenging to reliably provide without the necessary experience.

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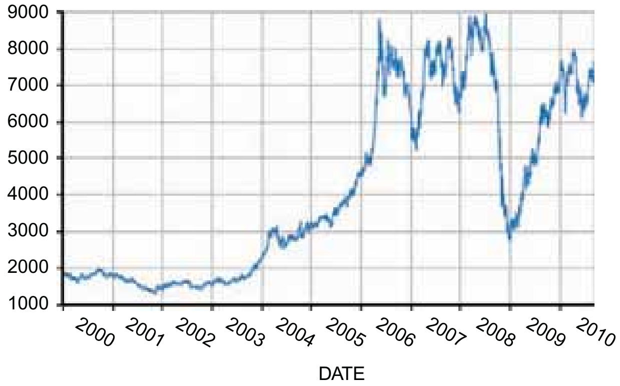

Fig. 1. Copper Grade A price graph in US$/t[1].

The objective of the present work was to find the most economic material configuration for a multi stage flash (MSF) desalination plant with a planned lifetime of thirty years based on data obtained from existing plants and to optimize the wall thickness requirements.

2. Literature review

The most cited reports were done by Arthur D. Little [2], in the course of which a survey of about 120 MSF desalination plants at 80 different locations was carried out and where failure rates for tubes made of aluminum brass, CuNi 90/10, CuNi 70/30 and CuNi 66/30/2/2 were collected. Although the survey covers a large number of plants the comparability to plants built nowadays had to be questioned. Particularly as the anti-scale treatment method changed from acid and polyphosphate to less corrosive polymers and as there was a change in carbon dioxide release. Carbon dioxide was vented off in the course of acid treatment, which was not the case for early polymer-treated plants. Carbon dioxide, when accumulated in the vapor zone forms carbonic acid, lowers the pH and causes cupronickel to corrode. This effect is empowered by the presence of oxygen. Without oxygen, even at low pH values, no corrosion would take place [2,3]. State of the art polymer treated plants are equipped with deaerators, where carbon dioxide and oxygen is removed in order to minimize corrosion risks.

From the Al-Jubail plant in the Kingdom of Saudi Arabia a sudden appearance of a very high number of tube failures in the first stage was reported which occurred after a period of about fourteen years on duty [4]. The reasons responsible for these failures were found to be a galvanic interaction between the tube sheets (SS 316L) and the tubes (90/10 CuNi) on the one hand and low pH due to carbon dioxide accumulation on the other hand. The accumulation was enabled by the lack of proper deaeration. Additionally, vibrations of the tubes could also be a reason.

3. Method

From the literature review no comparable surveys on tubing material performance in polymer treated plants could be made available. Instead, it was decided to use eddy current test data from three MSF desalination units (A, B and C) located in the Persian Gulf which were collected after an operation period of thirty (C) and thirty-four (A and B) years respectively.

3.1. Mean corrosion rate

Units A and B were of the brine recirculation cross-tube type with twenty-one heat recovery and three heat rejection stages, arranged in two tiers. Unit C was configured equally, except the heat rejection stages, of which it had four instead of three. All these units were operated at a maximum top brine temperature of 110 °C and a maximum capacity of about 27,000 tons per day, were polymer anti-scale treated and no deaeration was applied to the make-up seawater.

Tubing of the first two stages was made of 70/30 CuNi (UNS C71500) and stages three to twenty-two of the heat recovery section were made of aluminum brass (UNS C68700). The heat rejection section (stages 23 to 25 and 26 respectively) was equipped with 70/30 CuNi (UNS C71500) tubes. Cupronickel was used for the tubes sheets, whereas tube supports were made of carbon steel. Carbon steel was also used as shell material.

Eddy current test data were available for the aluminum brass (UNS C68700) tubing of stages four to twenty-two, classified into tubes with losses in wall thickness of 0 to 20%, 20 to 40%, 40 to 60%, 60 to 80% and 80 to 100% and into tubes which were plugged or could not be accessed. Fig. 2 exemplarily shows an eddy current test result of a single stage.

Based on these classes an annual mean corrosion rate was calculated, conservatively assuming the total corrosion rate to be at the maximum boundary of the respective range, as the distribution across the range could not reliably assessed. For example, each tube in class 20 to 40% was presumed to have a loss in wall thickness over the specified operation period of 40%. This leads to an average corrosion rate of 0.0163 mm/a, considering an initial wall thickness of 1.22 mm and an operation period of thirty years.

The mean corrosion rate for aluminum brass (UNS C68700) tubes is summarized in Table 1. Assuming x tubes of units A and B (34 years) and y tubes of unit C (30 years) in this class, the mean corrosion rate

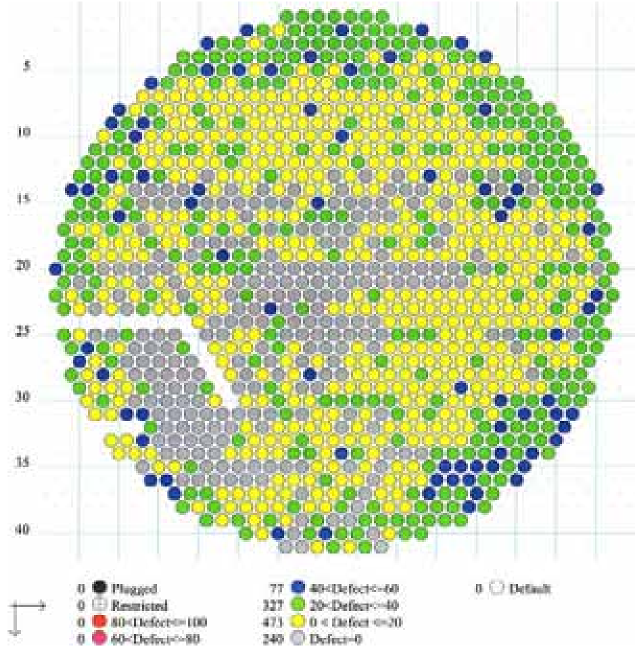

Fig. 2. Exemplary eddy current test result.

Table 1
Mean corrosion rate of aluminum brass (UNS C68700) tubes

Class, %	Maximum corrosion, mm	Corrosion rate for 34 years, mm/a	Corrosion rate for 30 years, mm/a	Mean corrosion rate, mm/a
0–20	0.244	$7.18e^{-03}$	$8.13e^{-03}$	$7.43e^{-03}$
20–40	0.488	$1.44e^{-02}$	$1.63e^{-02}$	$1.50e^{-02}$
40–60	0.732	$2.15e^{-02}$	$2.44e^{-02}$	$2.26e^{-02}$
60–80	0.976	$2.87e^{-02}$	$3.25e^{-02}$	$3.08e^{-02}$
80–100	1.220	$3.59e^{-02}$	$4.07e^{-02}$	$3.84e^{-02}$

was calculated by $(1.44e^{-2} * x + 1.63e^{-2} * y) / (x + y)$ for a particular stage. The mean corrosion rate as listed below was eventually obtained by averaging the mean corrosion rates of all stages within one class.

Mean corrosion rates in Table 1 are valid for aluminum brass (UNS C68700) tubes and had to be further adapted to all the other materials in question. To roughly assess the difference in corrosion rates of the different materials, ratios were taken out of Fig. 3. They were found to be some 0.5 for CuNi 90/10 (UNS C70600) and 0.33 for 70/30 CuNi (UNS C71500) after a period of thirty months. However, the curve of CuNi 90/10 shows a downward trend, so that a lower corrosion rate and therefore a lower ratio may be expected. Conservatively, all calculations herein are based on the ratio of 0.5.

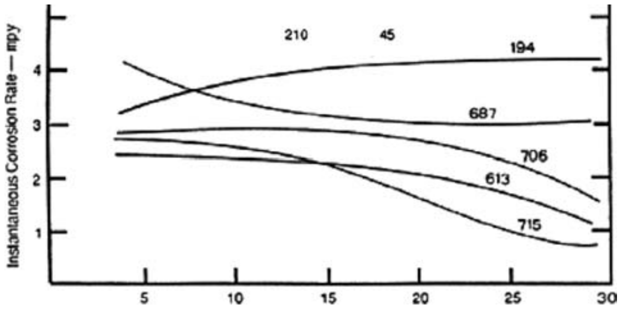

Fig. 3. Variation in corrosion rate for copper alloys from 5 to 30 months in the heat recovery section of an experimental desalination plant [2].

3.2. Exemplary multistage flash desalination plant

The current work is related to an exemplary multi-stage flash desalination plant with a maximum net capacity of 90,000 t/d, a top brine temperature of 113 °C maximum and a performance ratio of 9.8. The performance ratio was kept constant for the different tubing configurations investigated. Consequential changes in heat transfer area due to different thermal conductivities (different materials) and inner heat transfer coefficients (different inner diameters and therefore flow velocities) were balanced by adapting the number of tubes accordingly. The number of tubes was kept equal for all heat recovery stages and was kept equal for all heat rejection stages. Fig. 4 represents the schematic flow sheet of this plant, which is arranged in twenty-one heat recovery and two heat rejection stages.

Process data, in particular the temperatures and pressures prevailing and influencing the wall thickness calculation in the single stages, were obtained from OPUS™, an in-house developed software tool for simulating desalination and power plants of different types [5]. OPUS™ allows the user to simulate, optimize and compare any imaginable process configuration. Moreover, this comprehensive and powerful software tool combines thermodynamic simulation, CAPEX and OPEX estimation, financial modelling, plant optimization and life-cycle cost assessment for combined power and desalination plants.

3.3. Internal design pressure

The internal design pressure P was determined as the difference between the operating pressure inside the tubes and the minimum possible pressure at the outer side of the tubes, the so called steam side. For this pressure most severe conditions were assumed, prevailing whenever the unit is under full vacuum without any vaporization in the stages (start-up conditions). For full vacuum a pressure of 100 mbar (a) was taken into

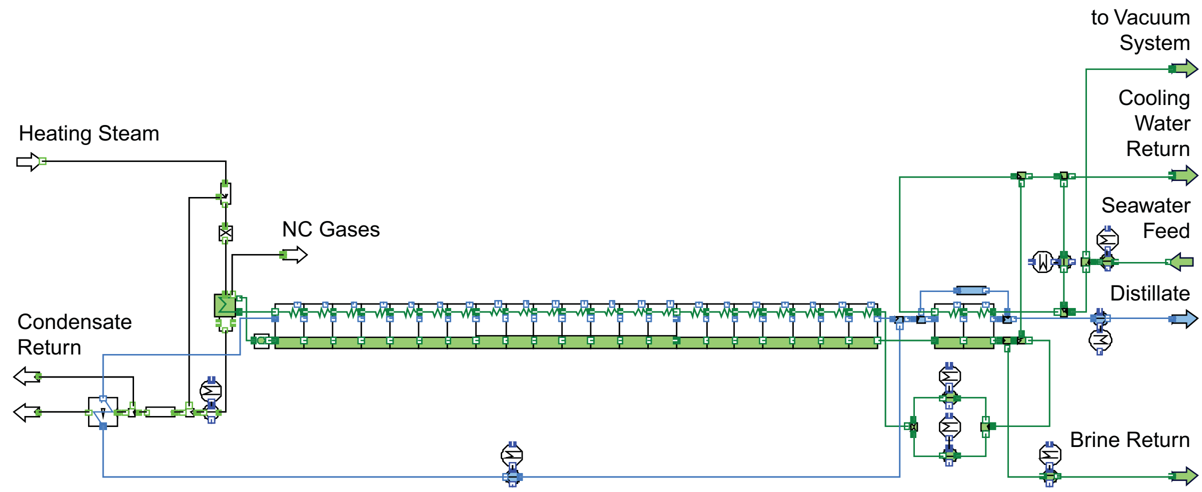

Fig. 4. Process flow diagram of exemplary multi-stage flash plant.

Table 2
Max allowable stress values [MPa] for CuNi 90/10 (UNS C70600) and CuNi 70/30 (UNS C71500) according to ASME II, Part D, Table 5b, 2007

Product form	Alloy desig./ UNS No.	Class/ cond./ temper	Min. tensile strength, MPa	Min. yield strength, MPa	Max. allowable stress value, MPa			
					40 °C	65 °C	100 °C	125 °C
Cond. tube	C70600	O61	275	105	68.9	67.0	65.0	63.6
Cond. tube	C71500	O61	360	125	82.7	79.9	77.5	75.9

consideration. For example, a water sided operating pressure of 4 bar (g) in stage 7 leads to an internal design pressure of 4.9 bar.

The pressure inside the tubes was assessed by evenly distributing the pressure loss to the different tube bundles, starting with 7.7 bar(g) upstream stage twenty-one and diminishing to some 1.9 bar(g) downstream of stage one. No detailed pressure loss calculation was carried out.

3.4. Maximum allowable stress value

Values for the maximum allowable stress S were taken from Table 2 for CuNi 90/10 (UNS C70600) and CuNi 70/30 (UNS C71500) considering the maximum temperature possible during normal operation and therefore most severe conditions, as the allowable stress values diminish with increasing temperature, although the maximum possible pressure difference is related to ambient conditions (full vacuum, no vapor present).

For aluminum brass Fig. 5 is valid as no accordant data are available within ASME II, Part D, Table 5b, 2007. The maximum allowable stress values of CuNi 66/30/2/2 (UNS C71640) were assumed to be almost equal to that of CuNi 70/30 (UNS C71500).

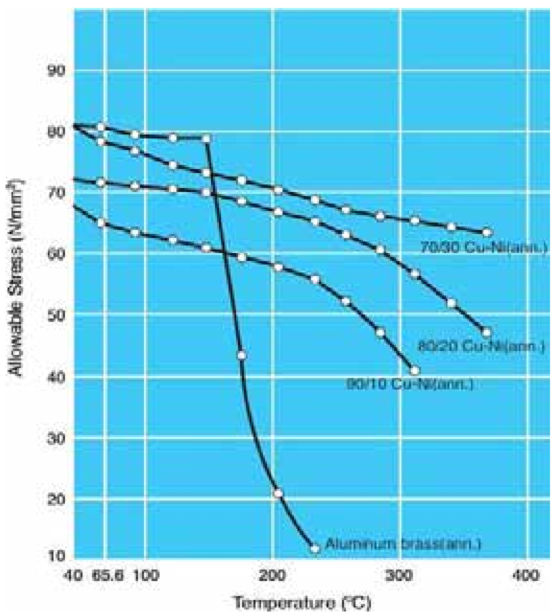

Fig. 5. Max allowable stress value [N/mm²] for aluminum brass (UNS C68700) according to Shinko, “Copper Alloy Tubes for Heat-Exchangers”, based on ASME VIII, 1989.

3.5. Minimum wall thickness

To get the minimum required wall thickness t of each single stage ASME VIII, Division 1, 2001 was drawn on

$$t = \frac{P \cdot R_o}{S \cdot E + 0.4 \cdot P} \tag{1}$$

With the already elucidated values for an internal design pressure P of 4.9 bar, a maximum allowable stress value S of about 80 N/mm² for aluminum brass and with an outer tube diameter of 50 mm the minimum wall thickness accounts for 0.153 mm as illustrated below.

$$t = \frac{4.9e^5[Pa] \cdot \frac{50[mm]}{2}}{80e^6[Pa] \cdot 1.0 + 0.4 \cdot 4.9e^5[Pa]} = 0.153 \text{ mm} \tag{2}$$

3.6. Minimum corrosion allowance

The minimum required corrosion allowance was calculated from the mean corrosion rates obtained from reference plant data evaluation, accepting a tube failure rate of not more than 6% per stage.

Considering the entire number of tubes in a specific stage (all three investigated units) distributed to the different classes as exemplarily depicted for stage 7 in Table 3, than 1.3% of tubes would show a maximum reduction in tube wall thickness somewhere between 80% and 100% and 4.2% show a reduction of 60%–80%. Outfitting the tubes with a corrosion allowance equivalent to 60% of the tube wall thickness would mean 5.6% (≤ 6%) of tubes could fail during the operation period. Taking into account 0.1% of plugged and not accessible tubes, the percentage raises to 5.7%.

The required minimum corrosion allowance was calculated by using the mean corrosion rate of the respective class ($2.26e^{-2}$ mm/a, see also section 3.1) multiplied by the years of planned plant lifetime ($2.26e^{-2}$ mm/a × 30 years = 0.678 mm).

3.7. Required wall thickness

The minimum required tube wall thickness was eventually obtained by adding up the minimum wall thickness according to ASME (see section 3.5) and the minimum required corrosion allowance (see section 3.6). For the exemplary stage the required wall thickness accounts for 0.153 mm + 0.678 mm = 0.831 mm, provided that the tube is made of aluminum brass.

3.8. Economic evaluation

The economic evaluation is based on manufacturers' proposals for the materials in question collected for different tube diameters and wall thicknesses over the last view years. Prices per unit were inflation-adjusted, corrected by currency fluctuations and updated via LME rates [1]. Eventually, they were extrapolated for tube wall thicknesses and tube diameters required. Unit prices obtained as described were used to calculate price differences of different tubing configurations and to determine the most economical solution.

4. Results

In the course of the refurbishment works some internals had to be replaced, in particular the distillate trough (carbon steel) of stages one and two, which suffered from severe corrosion. Problems were also reported for the first three stages, where a number of tubes failed and were plugged during the years (some 7–10%). Most of these plugged tubes were located close to the baffle plates. No galvanic interaction between tubes and tube support plates could be observed. All these corrosion problems were not investigated further in detail and are solely quoted here for the sake of completeness.

The eddy current test results of the investigated units are illustrated in Figs. 6–8. The figures represent the numbers of tubes within the predefined classes of 0–20%, 20–40%, 40–60%, and 60–80% and 80–100% loss in tube wall thickness over the respective operation period in stages four to twenty-two. They also show the number of tubes plugged as well as the number of tubes with restricted access. Desalination units A and B were operated for a period of 34 years, unit C for a period of about 30 years.

From Figs. 6 and 7 it can be seen that only a marginal number of tubes in unit A and B held a loss in wall thickness of more than 60%, whereas unit C (Fig. 8) showed a considerably higher rate even for a loss of 80%. However, only stage numbers lower than 12 were affected.

Table 3
Distribution of all tubes of stage 7 to the different, predefined classes

Class	0–20%	20–40%	40–60%	60–80%	80–100%	Plugged or not accessible
Relative frequency	100%	59.1%	19.8%	5.7%	1.4%	0.1%

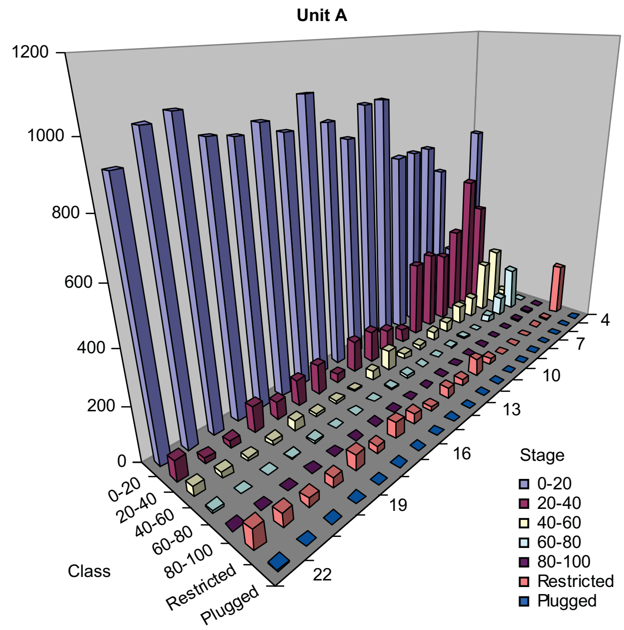

Fig. 6. Eddy current test results unit A.

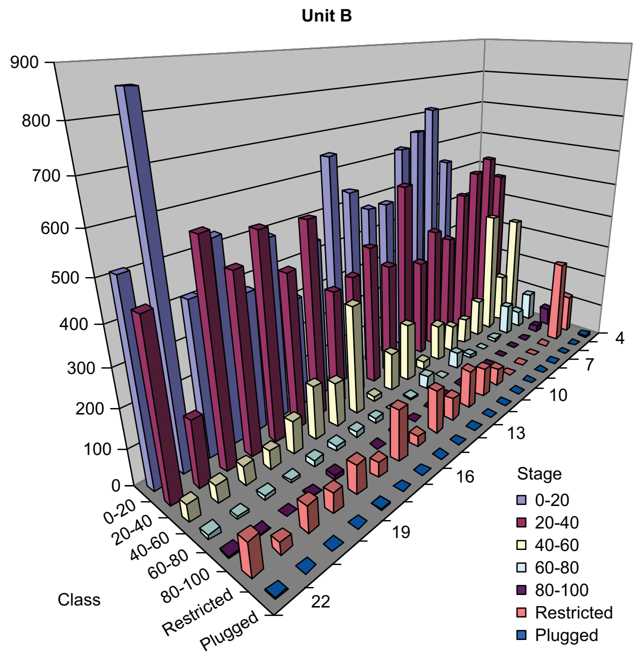

Fig. 7. Eddy current test results unit B.

4.1. Single stage recommendations

Calculations were carried out for each single stage, however, only the most significant are shown in the following. Stages were deemed to be most significant whenever a change in wall thickness or material selection became recommendable.

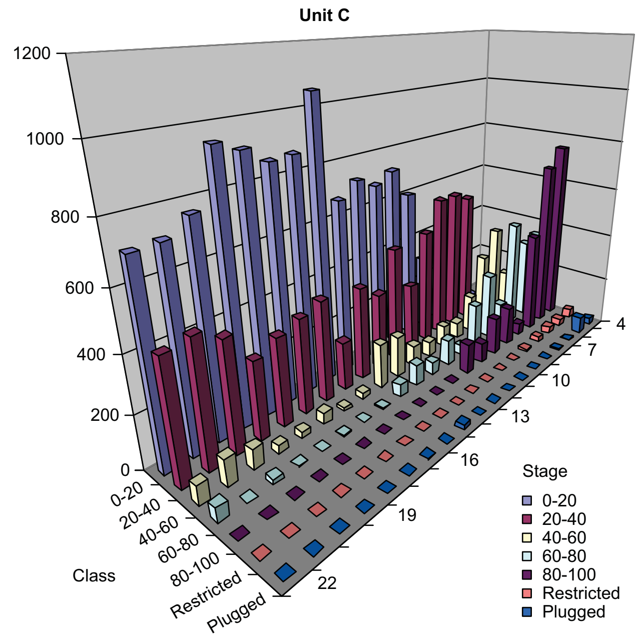

Fig. 8. Eddy current test results unit C.

4.2. Stage 1

The calculation of the minimum tube wall thickness required in stage 1 is based on following conditions:

4.2.1. Internal design data

Pressure inside tubes	2.4	bar(g)
Pressure outside tubes	–0.9	bar(g)
Design pressure difference	3.3	bar(g)
Stage temperature	113.0	degC

4.2.2. Maximum allowable stress value and minimum wall thickness

Table 4
Maximum allowable stress value and minimum wall thickness stage 1

Tube material UNS	Al-Brass C68700	CuNi9010 C70600	CuNi7030 C71500	CuNi6630 C71640
Max allowable stress value (UG-23/UG-24), MPa	79.5	64.3	76.6	76.6
Joint efficiency	1.0	1.0	1.0	1.0
Min. thickness required, mm	0.104	0.129	0.108	0.108

Table 5
Required wall thickness stage 1

Tube material UNS		Al-Brass C68700	CuNi9010 C70600	CuNi7030 C71500	CuNi6630 C71640	
0–20%	mm	0.327	0.241	0.175	0.175	100.0%
20–40%	mm	0.556	0.355	0.244	0.244	73.8%
40–60%	mm	0.783	0.469	0.312	0.312	55.0%
60–80%	mm	1.029	0.591	0.386	0.386	40.4%
80–100%	mm	1.256	0.705	0.454	0.454	26.6%
Plugged	mm					0.9%

4.2.3. Required Wall Thickness

In order to fulfill the restriction of accepting not more than 6% tube failures, a mean corrosion rate of $3.48e^{-2}$ mm/a had to be considered (see Table 1), resulting in a required wall thickness of 1.256 mm for tubes made of aluminum brass (UNS C68700) for instance (see Table 5). Accordingly, for 90/10 CuNi the required wall thickness would be 0.705 mm. In both cases a theoretical tube failure rate of 0.9% has to be expected.

In the absence of eddy current test results for stages 1 to 3 the distribution of stage 4 was applied to these stages (Fig. 9). Independent of the effectively predominating distribution in these stages the result remains almost unaffected, as stage 4 already requires the maximum mean corrosion rate.

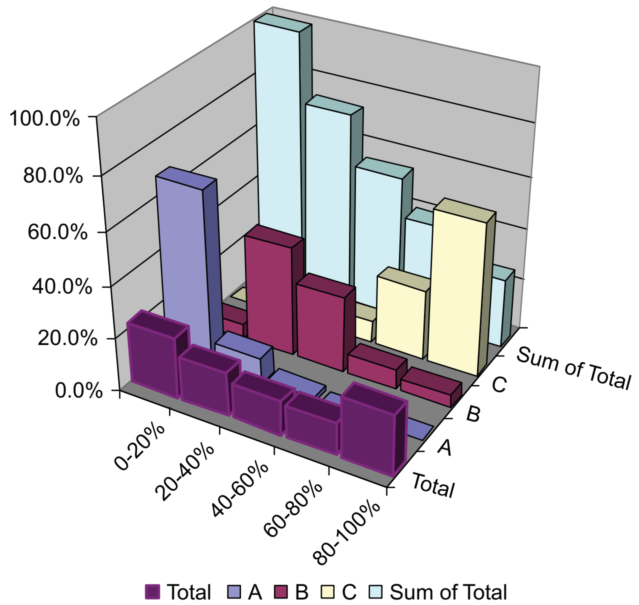

Fig. 9. Relative number of tubes in predefined classes for units A, B and C of stage 4.

4.3. Stage 4

4.3.1. Internal design data

Pressure inside tubes	3.2	bar(g)
Pressure outside tubes	–0.9	bar(g)
Design pressure difference	4.1	bar(g)
Stage temperature	95.0	degC

4.3.2. Maximum allowable stress value and minimum wall thickness

Table 6
Maximum allowable stress value and minimum wall thickness stage 4

Tube material UNS	Al-Brass C68700	CuNi9010 C70600	CuNi7030 C71500	CuNi6630 C71640
Max allowable stress value (UG-23/UG-24), MPa	79.5	65.3	77.8	77.8
Joint efficiency	1.0	1.0	1.0	1.0
Min. thickness required, mm	0.129	0.157	0.132	0.132

4.3.3. Required wall thickness

Table 7
Required wall thickness stage 4

Tube material UNS		Al-Brass C68700	CuNi9010 C70600	CuNi7030 C71500	CuNi6630 C71640	
0–20%	mm	0.352	0.269	0.199	0.199	99.9%
20–40%	mm	0.580	0.383	0.267	0.267	73.8%
40–60%	mm	0.808	0.497	0.336	0.336	55.0%
60–80%	mm	1.054	0.620	0.409	0.409	40.4%
80–100%	mm	1.281	0.733	0.477	0.477	26.6%
Plugged	mm					0.9%

4.4. Stage 6

4.4.1. Internal design data

Pressure inside tubes	3.7	bar(g)
Pressure outside tubes	–0.9	bar(g)
Design pressure difference	4.6	bar(g)
Stage temperature	88.3	degC

4.4.2. Maximum allowable stress value and minimum wall thickness

Table 8
Maximum allowable stress value and minimum wall thickness stage 6

Tube material UNS	Al-Brass C68700	CuNi9010 C70600	CuNi7030 C71500	CuNi6630 C71640
Max allowable stress value (UG-23/UG-24), MPa	79.8	65.7	78.3	78.3
Joint efficiency	1.0	1.0	1.0	1.0
Min. thickness required, mm	0.145	0.176	0.148	0.148

4.4.3. Required wall thickness

Table 9
Required wall thickness stage 6

Tube material UNS		Al-Brass C68700	CuNi9010 C70600	CuNi7030 C71500	CuNi6630 C71640	
0–20%	mm	0.368	0.288	0.215	0.215	100.0%
20–40%	mm	0.596	0.402	0.283	0.283	89.2%
40–60%	mm	0.824	0.516	0.352	0.352	57.8%
60–80%	mm	1.070	0.639	0.425	0.425	29.5%
80–100%	mm	1.297	0.752	0.493	0.493	11.9%
Plugged	mm					0.1%

4.5. Stage 7

4.5.1. Internal design data

Pressure inside tubes	4.0	bar(g)
Pressure outside tubes	–0.9	bar(g)
Design pressure difference	4.9	bar(g)
Stage temperature	85.1	degC

4.5.2. Maximum allowable stress value and minimum wall thickness

Table 10
Maximum allowable stress value and minimum wall thickness stage 7

Tube material UNS	Al-Brass C68700	CuNi9010 C70600	CuNi7030 C71500	CuNi6630 C71640
Max allowable stress value (UG-23/UG-24), MPa	80	65.9	78.5	78.5
Joint efficiency	1.0	1.0	1.0	1.0
Min. thickness required, mm	0.153	0.186	0.156	0.156

4.5.3. Required wall thickness

Table 11
Required wall thickness stage 7

Tube material UNS		Al-Brass C68700	CuNi9010 C70600	CuNi7030 C71500	CuNi6630 C71640	
0–20%	mm	0.376	0.297	0.223	0.223	100.0%
20–40%	mm	0.604	0.411	0.291	0.291	59.1%
40–60%	mm	0.832	0.525	0.360	0.360	19.9%
60–80%	mm	1.078	0.648	0.433	0.433	5.7%
80–100%	mm	1.305	0.762	0.501	0.501	1.4%
Plugged	mm					0.1%

Accepting a tube failure rate of 6% only leads to a minimum wall thickness of 0.832 mm in case of aluminum brass and 0.525 mm in case of 90/10 CuNi. When taking a closer look at Fig. 9 to Fig. 11 it is getting obvious that the distribution towards a comparatively high number of tubes in class 80 - 100% is mainly driven by unit C. For stages up to number six (Fig. 9 and Fig. 10) the contribution of unit C is significant, for stage seven (Fig. 11) and the following stages unit C is still trend-setting, but much less significant.

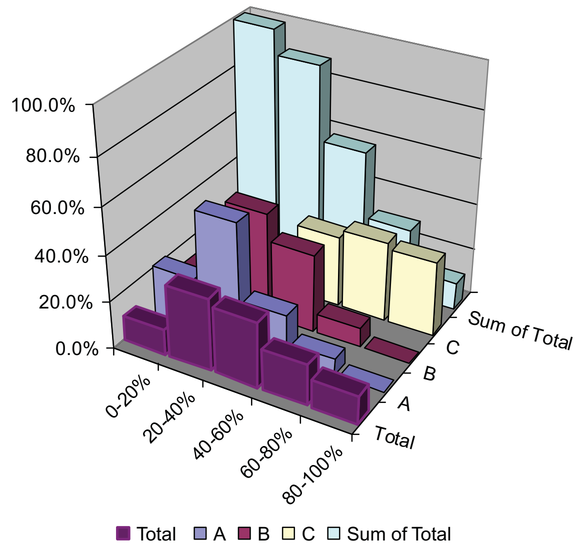

Fig. 10. Relative number of tubes in predefined classes for units A, B and C of stage 6.

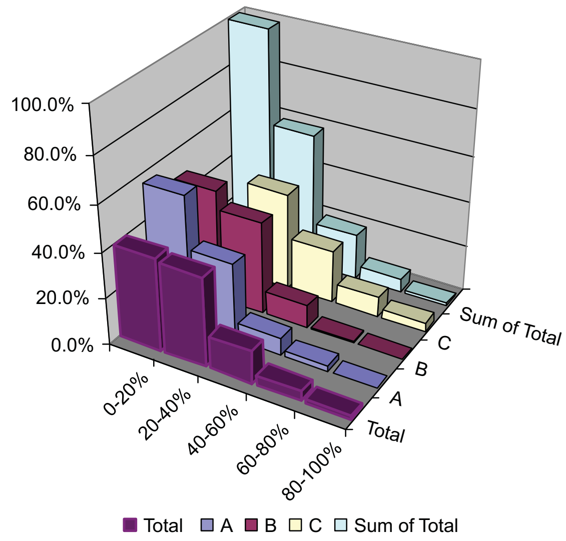

Fig. 11. Relative number of tubes in predefined classes for units A, B and C of stage 7.

4.6. Stage 10

4.6.1. Internal design data

Pressure inside tubes	4.8	bar(g)
Pressure outside tubes	–0.9	bar(g)
Design pressure difference	5.7	bar(g)
Stage temperature	75.8	degC

4.6.2. Maximum allowable stress value and minimum wall thickness

Table 12
Maximum allowable stress value and minimum wall thickness stage 10

Tube material UNS	Al-Brass C68700	CuNi9010 C70600	CuNi7030 C71500	CuNi6630 C71640
Max allowable stress value (UG-23/UG-24), MPa	80	66.4	79.2	79.2
Joint efficiency	1.0	1.0	1.0	1.0
Min. thickness required, mm	0.178	0.214	0.179	0.179

4.6.3. Required wall thickness

For stage 10 the class of tubes with a loss in wall thickness of more than 60% is less than 5%, so that the minimum required wall thickness for aluminum brass tubes is assessed with 0.857 mm. For CuNi 90/10 a wall thickness of 0.553 mm is sufficient (Table 13 and Fig. 12).

Table 13
Required wall thickness stage 10

Tube material UNS		Al-Brass C68700	CuNi9010 C70600	CuNi7030 C71500	CuNi6630 C71640	
0–20%	mm	0.400	0.325	0.246	0.246	100.0%
20–40%	mm	0.629	0.439	0.315	0.315	42.8%
40–60%	mm	0.857	0.553	0.383	0.383	11.7%
60–80%	mm	1.102	0.676	0.457	0.457	4.9%
80–100%	mm	1.329	0.790	0.525	0.525	2.4%
Plugged	mm					0.0%

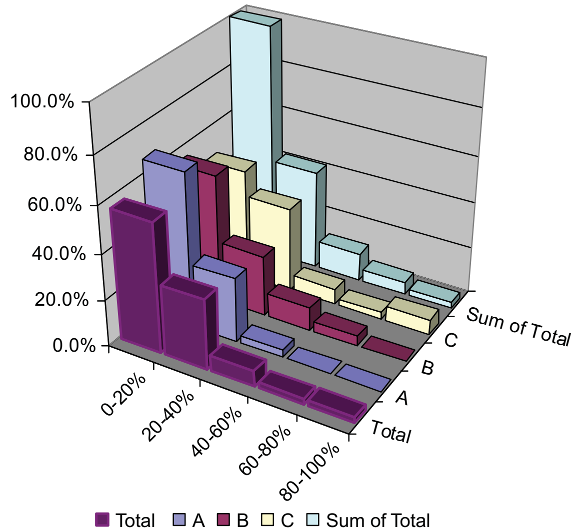

Fig. 12. Distribution of number of tubes to defined classes for units A, B and C of stage 10.

4.7. Stage 21

4.7.1. Internal design data

Pressure inside tubes	7.7	bar(g)
Pressure outside tubes	–0.9	bar(g)
Design pressure difference	8.6	bar(g)
Stage temperature	44.6	degC

4.7.2. Maximum allowable stress value and minimum wall thickness

Table 14
Maximum allowable stress value and minimum wall thickness stage 21

Tube material UNS	Al-Brass C68700	CuNi9010 C70600	CuNi7030 C71500	CuNi6630 C71640
Max allowable stress value (UG-23/UG-24), MPa	81	68.5	82.1	82.1
Joint Efficiency	1.0	1.0	1.0	1.0
Min. thickness required, mm	0.264	0.312	0.261	0.261

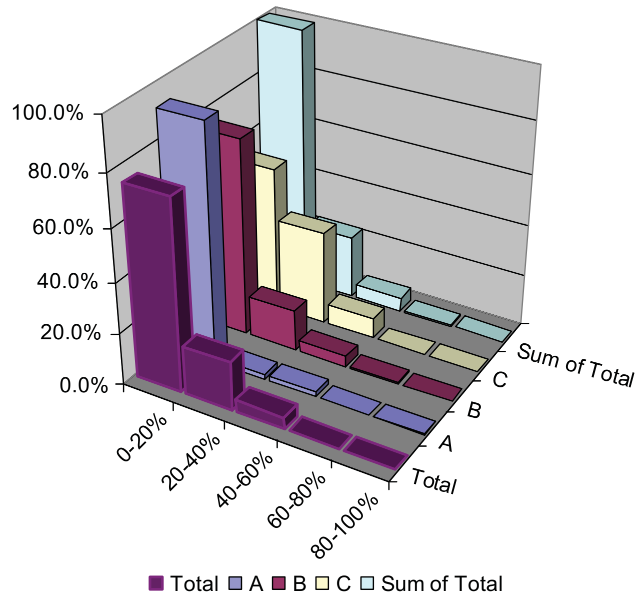

Fig. 13. Distribution of number of tubes to defined classes for units A, B and C of stage 21.

4.7.3. Required wall thickness

Fig. 13 reflects what was readily identifiable from Figs. 6-8. Only a small number of tubes show a loss in wall thickness of more than 60%. Consideration of a maximum number of tube failures of not more than 6% leads to a required minimum wall thickness of 0.715 mm for aluminum brass and 0.538 mm for 90/10 CuNi tubes.

5. Conclusion and recommendations

From the computations carried out changes in tubing configuration got necessary in stages 4, 7 and 10, so that tubes of stages 2 and 3 were equipped with material and wall thickness equal to that of stage 1. Similarly, tubes of stages 5 and 6 were configured equal to stage 4 and tubes of stages 8 and 9 were configured equal to stage 7. For stages 11 to 21 tube configuration of stage 10 was applied.

Calculations based on corrosion rates taken from stages 4 of the reference plants for stage 1 brought out a minimum required wall thickness of 1.256 mm for aluminum brass and 0.705 mm for 90/10 CuNi. For stage 4 the minimum required tube wall thickness was determined with 1.281 mm for aluminum brass and with 0.733 mm for 90/10 CuNi, whereas 0.832 mm in case of aluminum brass and 0.525 mm in case of 90/10 CuNi were obtained for stage 7. Calculations for stage 10 resulted in 0.857 mm for aluminum brass and 0.553 mm for 90/10 CuNi.

Table 16 depicts the cost assessment for a tube configuration based on minimum required wall thicknesses obtained for 90/10 CuNi. Table 17 represents figures carrying out the same for aluminum brass. From both tables it gets obvious that the CuNi 90/10 configuration is economically more efficient than the aluminum brass configuration, which is some 15% higher in costs.

Table 15
Required wall thickness stage 21

Tube material UNS		Al-Brass C68700	CuNi9010 C70600	CuNi7030 C71500	CuNi6630 C71640	
0–20%	mm	0.487	0.424	0.328	0.328	100.0%
20–40%	mm	0.715	0.538	0.396	0.396	24.5%
40–60%	mm	0.943	0.652	0.465	0.465	5.3%
60–80%	mm	1.189	0.775	0.538	0.538	0.4%
80–100%	mm	1.416	0.888	0.606	0.606	0.1%
Plugged	mm					0.1%

Table 16
Cost assessment for a tube configuration based on minimum required tube wall thicknesses obtained for CuNi 90/10

Stage	To stage	Material	Tube OD, mm	Tube length, m	Wall thick, mm	Tubes per stage	Total cost, $k
1	3	CuNi 90/10	50.0	25.0	0.71	2,546	1,731
4	6	CuNi 90/10	50.0	25.0	0.73	2,546	1,657
7	9	CuNi 90/10	50.0	25.0	0.53	2,546	1,374
10	21	CuNi 90/10	50.0	25.0	0.55	2,546	5,728
22	23	CuNi 70/30	40.0	25.0	0.90	3,540	1,791
Total							12,281

Table 17
Cost assessment for a tube configuration based on minimum required tube wall thicknesses obtained for aluminum brass

Stage	To stage	Material	Tube OD, mm	Tube length, m	Wall thick, mm	Tubes per stage	Total cost, $k
1	3	Al Brass	50.0	25.0	1.26	2,492	1,964
4	6	Al Brass	50.0	25.0	1.28	2,492	1,961
7	9	Al Brass	50.0	25.0	0.83	2,492	1,545
10	21	Al Brass	50.0	25.0	0.86	2,492	6,892
22	23	CuNi 70/30	40.0	25.0	0.90	3,540	1,791
Total							14,153

Table 18
Cost assessment for the recommended tube configuration

Stage	To stage	Material	Tube OD, mm	Tube length, m	Wall thick, mm	Tubes per stage	Total cost, $k
1	3	CuNi 90/10	50.0	25.0	0.90	2,522	2,138
4	6	CuNi 90/10	50.0	25.0	0.90	2,522	2,138
7	9	Al Brass	50.0	25.0	0.90	2,522	1,786
10	21	Al Brass	50.0	25.0	0.90	2,522	7,145
22	23	CuNi 70/30	40.0	25.0	0.90	3,540	1,791
Total							14,998

Considering more severe conditions in stages 1 to 3 than in stage 4 a tube material of higher quality is recommendable and a certain safety margin in terms of wall thickness should be provided. For lack of respective data corrosion rates of stage 4 were drawn on for these stages, as already mentioned above. Considering moreover a minimum practicable tube wall thickness of 0.9 mm related to an outer tube diameter of 50 mm for both materials, restricted in terms of producibility and further processability (e.g. transportation and/or assembly), a tube configuration of 0.9 mm wall thickness and 90/10 CuNi was chosen for these stages.

For stages 4 to 6 a tube configuration of 1.28 mm thick aluminum brass tubes would last for the required lifetime of thirty years. Comparing an evaporator configuration using aluminum brass for these stages with one utilizing 90/10 CuNi instead, shows a slight advantage of some 1.5% for the former. However, due to the smaller total flow section narrowed by the larger wall thickness and the lower number of tubes, more power for pumping is required (some 1.7%), so that the savings in capital expenditures are nullified by additional operational expenditures within the lifetime of the plant.

The tube wall thickness for the remaining heat recovery stages is restricted by the minimum practicable diameter of 0.9 mm, so that tubes of aluminum brass are favorable.

Due to costs exceeding those of both the other materials by some 30-40%, 70/30 CuNi was deemed to be not economical for the heat recovery section. In the given comparison it was used for the heat recovery section, however without being investigated in more detail. The configuration for the heat recovery section remained unchanged in all cases.

Table 18 represents the tubing configuration obtained from above considerations. However, it has to be noted that the given tubing configuration is process data specific and not valid in general as the process parameters might change for different constraints. For optimization reasons the tubing configuration should be rechecked for each individual case.

Symbols

E	—	Joint efficiency for, or the efficiency of, appropriate joint in cylindrical or spherical shells, of the efficiency of ligaments between openings, whichever is less. For welded vessels, use the efficiency specified in UW 12. For ligaments between openings, use the efficiency calculated by the rules given in UG 53.
P, Pa	—	Initial design pressure (according to UG 21)

R_0, mm — Inside radius of the shell course under consideration.

S, Pa — Maximum allowable stress value (according to UG 23 and the stress limitations specified in UG 24)

T, mm — Minimum required thickness of wall

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