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AECU-3246

ENGINEERING

UNITED STATES ATOMIC ENERGY COMMISSION

PERFORMANCE OF FALLING-FILM
EVAPORATOR IN CONCENTRATING
SYNTHETIC WASTE SOLUTIONS

By
H. C. Harrison
P. J. Hess
H. T. Tupper

April 8, 1950

Engineering Practice School
Massachusetts Institute of Technology
Oak Ridge, Tennessee

Technical Information Service Extension, Oak Ridge, Tenn.

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CARBIDE AND CARBON CHEMICALS DIVISION
Union Carbide and Carbon Corporation

MEMORANDUM

EPS-X83

AFCU-3246

April 8, 1950

TO: T. H. Pigford
FROM: H. C. Harrison, P. J. Hess, and H. T. Tupper
SUBJECT: Performance of Falling-Film Evaporator in Concentrating Synthetic Waste Solutions

INTRODUCTION

One step in the disposal of radioactive waste solutions at X-10 is concentration by evaporation. This concentration decreases the space required for storage while the radioactive particles are decaying. Currently, shell and tube evaporators are used; however, due to excessive foaming and entrainment, radioactive condensates are often produced. Unfortunately, these condensates when radioactive require decontamination and storage space. Consequently, the use of a "falling film" evaporator has been proposed to eliminate radioactive condensates. This type evaporator was chosen because it entailed evaporation or boiling from a thin falling film and not from a relatively stagnant body of liquid. A bubble when formed does not travel far before it escapes to the vapor, and slugging and consequent entrainment are reduced. Also, because the fluid is in motion as a freely falling film, foaming is less likely to occur. By virtue of the above two facts, no entrainment, and consequently no condensate contamination, is expected.

The evaporator and other equipment were designed and built by Chapman, Griffith, and Jasny (1). The flow sheet is shown in Fig. 1.

[1]

2 23

1 2468

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As a step in determining the feasibility of a falling film evaporator for plant operation, this work was to determine:

1. Best operating conditions to prevent excessive salt crystallization on the evaporator surfaces.
2. Heat transfer coefficients for the evaporator as a function of liquid flow rate, temperature differentials, and solution concentration.
3. Effect of vapor velocity on evaporating characteristics; i.e., entrainment.

The investigation was conducted from March 23 to April 7, 1950.

RESULTS AND DISCUSSION OF RESULTS

Crystallization on Heating Surface

Data for this investigation were taken over the following ranges: peripheral flow rates from 134.1 to 931.5 lb/(hr)x(ft), rates of evaporation from 0.202 to 0.627 lb/min, and feed concentrations from 2 to 50 lb NaNO₃/100 lb H₂O.

Over these ranges no crystallization of sodium nitrate occurred on the walls of the evaporator. This was expected, since neither the feed solution nor the concentrate was saturated with sodium nitrate.

Heat Transfer Coefficients

Table I summarizes the heat transfer coefficients obtained. The highest value obtained for the heat transfer coefficient was 1560 Btu/(hr)(sq ft) (F), while the lowest was 924. Plots of the coefficient against temperature drop for the four concentrations employed showed that the data scattered markedly (see Fig. 1). For a feed concentration of 25 lb NaNO₃/100 lb H₂O the lowest flow rate gave the lowest coefficients, the highest rate gave intermediate ones, and the intermediate flow rate gave the highest values. Using a 50 lb NaNO₃/100 lb H₂O, the values corresponding to the intermediate rate were the lowest and those for the low and high rates were about the same for a given ΔT . Since it seems unlikely that the coefficients would change greatly in their relative magnitude as the result of concentration change alone, the reliability of the numerical values obtained appeared to be in question. The precision analysis of the data, Appendix B, showed that the values obtained for the coefficients might be expected to vary by 22%. Therefore, the scattering of the data was not surprising. Most of the lack of precision in the values for h may be traced to the effect of variation in wall temperature readings on the value of ΔT . If ΔT had been much larger than about 6 F, the effect of such variation would have been less.

ADAPTED FROM EPS-X81

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FLOW SHEET FOR FALLING - FILM EVAPORATOR

DATE 3-22-50	DRAWN BY A.I.C.	FILE NO. EPS-X83	FIG. 1
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The average value of the thirty-one coefficients, 1225 Btu/(hr)(sq ft)(F), is certainly valuable from the standpoint of preliminary calculations.

Table II showing coefficients for various concentrations, temperature difference between the tube wall and the falling liquid layer, and flow rates was also prepared. The apparent variation of coefficients with ΔT , at a constant flow rate, is seen in this table. In four of the five instances in which three values of flow rates were available coefficients increased to a maximum at intermediate flow rates and decreased at higher rates. As a result of the poor precision, little importance can be attached to these variations.

A logarithmic plot of the coefficients versus the peripheral flow rates, Fig. 2, compared the data with the equation cited by McAdams (2),

$$h = 120 \Gamma^{1/3}.$$

This equation was based on data obtained from heating of water falling freely down the surface of vertical tubes.

The data indicate that the heat-transfer coefficients remained essentially constant at 1225 Btu/(hr)(sq ft)(F) even though the peripheral flow rate changed. The fact that the coefficients were higher than those indicated by the McAdams equation may be due to a different mechanism of heat transfer. These data were taken for fluid films under boiling conditions whereas the McAdams correlation is for the heating of liquids below their boiling point.

Effect of Vapor Velocities on Entrainment

In practically every run the entrainment was less than 0.0005 ± 0.00001 lb NaNO₃/lb of distillate solution. The maximum entrainment was 0.00175 lb NaNO₃/lb soln. However, none of these values is considered correct; the upper limit of entrainment is merely indicated. Inspection of the data shows that the entrainments are not comparable with regard to evaporation rates, i.e., in many cases higher entrainments are found in runs with low evaporation rates, and correspondingly low vapor velocities, than are found in runs with high evaporation rates. Furthermore, it is noticed that entrainments are high at the beginning of a series of runs and become progressively lower. This is attributed to the fact that when starting the equipment, slugs of steam were usually emitted from the feed preheater which caused splashing of the feed up into the condensate lines. After equilibrium was attained this misplaced feed would cause the first run of the series to be slightly contaminated, but consequent runs would become less contaminated as the feed was washed from the condensate lines. Therefore, it is assumed that essentially no entrainment is encountered by the process of evaporation, but rather by the process of splashing. However, at greater evaporation rates entrainment could become noticeable.

Table I

Summarized Results

Run No.	Peripheral Flow lb/(hr)(ft)	ΔT (F)	Heat-transfer Coefficient Btu/(hr)(sq ft)(F)	NaNO ₃ Entrainment in Condensate (wt %)
1	164.5	6.0	1200	0.000
2	171.4	8.2	1320	0.000
3	134.1	13.0	1086	0.000
4	164.1	5.7	1180	0.015
5	170.4	8.8	1190	0.013
6	155.3	11.0	1230	0.008
7	709.8	11.2	1175	0.004
8	704.2	7.8	1300	0.002
9	708.7	5.8	1120	0.004
10	324.9	5.4	1218	0.004
11	320.5	7.8	1344	0.000
12	321.6	9.0	1490	0.004
13	316.1	12.2	1380	0.003
14	731.9	5.3	1230	0.021
15	171.6	5.9	1024	0.175
16	165.2	8.2	1193	0.025
17	353.8	10.3	938	0.000
18	350.4	7.0	924	0.050
19	710.9	8.5	1223	0.000
20	708.7	10.4	1315	0.025
21	703.1	6.3	1118	0.038
22	311.1	5.4	1100	0.050
23	308.3	7.1	1470	0.050
24	320.5	9.6	1400	0.000
25	170.1	11.4	1180	0.025
26	177.4	10.4	962	0.025
27	168.6	6.5	1015	0.000
28	981.5	3.6	1590	0.050
29	672.1	4.8	1124	0.025
30	680.9	8.6	1145	0.025
31	582.2	9.9	1360	0.025

No crystallization of sodium nitrate on the walls of the evaporator was noticed during any of the runs.

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4 5 6 7 8 9 10 11 12 13 14

ΔT, F

h, BTU/HR-SQ FT-F

h, BTU/HR-SQ FT-F

1500
1400
1300
1200
1100
1000
900

1600
1500
1400
1300
1200
1100
1000
900

4 5 6 7 8 9 10 11 12 13 14

ΔT, F

KEY

- LOW FLOW RATES 1.5 LB/MIN
- ◐ MEDIUM FLOW RATES 3.0 LB/MIN
- HIGH FLOW RATES 6.5 LB/MIN

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PLOT OF FILM COEFFICIENT, h , VS
TEMPERATURE DIFFERENCE, ΔT , FOR
VARYING CONCENTRATION AND FLOW RATE

DATE 4-7-50	DRAWN BY HCH & PJH	FILE NO. EPS K83	P.L.D. 2
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Table II

Approximate Grouping of Data

Concentration of Feed (lb of NaNO ₃ per 100 lb of H ₂ O)	Approximate ΔT (F)	Heat-transfer Coefficients Btu/(hr)(sq ft)(F) at Indicated Approximate Flow Rates (lb/min)		
		1.5	3	6.5
2	6	1200	*	1230
	8.5	1320	*	*
	11	1086	*	*
8.43	6	1180	1218	1120
	8.5	1190	1344	1300
	11	1230	1380	1175
25	6	1015	1100	1124
	8.5	*	1470	1145
	11	1180	1400	1360
50	6	1024	924	1118
	8.5	1193	*	1223
	11	*	938	1315

* These data were not taken.

Suggested Changes in Equipment

To increase the range of fluid flow, installation of a small surge tank at the top of the feed standpipe is recommended. This would allow full use of the head available in the standpipe without fear of spilling solution from the top of the pipe.

The capacity of the feed preheater should be greatly reduced. This would

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KEY

- EXPERIMENTAL RESULTS
- BASED ON EXPERIMENTAL RESULTS
- BASED ON McADAMS EQUATION FOR HEATING WATER

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PLOT OF FILM COEFFICIENT, h
VS. FLOW RATE

DATE
4-7-50

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EPS K83

FIG.
3

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eliminate the steam slugging in the feed lines which caused erratic entrainment indications. Also, the feed temperature could be both more accurately controlled and brought closer to the boiling point. The recommended action would be to reduce greatly the heat-transfer area within the preheater.

The equipment leaked very slightly at several thermocouple inlets and at the top flange weld on the evaporator tube. These leaks caused the asbestos insulation of the heating coils to become soaked with sodium nitrate solution, a very good electrolyte. The result was that the heating coils became grounded through the copper evaporator tube, overheated and melted. Before data on the existing apparatus can be efficiently taken, these leaks must be repaired.

Increased heat flux, and consequently greater evaporation rates and ΔT 's may be obtained by replacing the existing electric heating coils with a steam jacket. Moreover, the use of steam as a heating medium would more nearly approximate industrial operations. To investigate the feasibility of a steam jacket a preliminary calculation was completed on the total heat-transfer coefficient. Using process steam at 100 psig, an average film coefficient of 1200 Btu/(hr)(sq ft)(F) for the feed solution, and a boiling point of 225 F, an overall coefficient of 578 Btu/(hr)(sq ft)(F) was calculated. This led to an expected heat flow of 162,400 Btu/hr as compared to a heat flow of 40,900 Btu/hr for the existing equipment.

PROCEDURE

Test runs made with water indicated the need for some minor changes in the apparatus. Wire screening was placed around the weir to prevent slugging of steam bubbles from the preheater from causing uneven fluid flow over the weir, and additional heating coils were placed on the evaporation column to increase its capacity.

A synthetic waste solution of the desired concentration was prepared from sodium nitrate and water. A particular flow rate was selected, and the heat input was varied for a number of runs, usually three. The flow rate was then changed, and another series of runs were taken at heat inputs corresponding to those of the first series of runs. A third flow rate was then selected. This procedure was repeated for four different solution concentrations. At each concentration the flow rates and heat inputs were approximately equal.

Data taken for each run were: tube-wall and vapor thermocouple readings, meter readings to determine electric power input, temperature of preheated feed, weights of condensate and concentrated solution, and the time duration.

Entrainment in the condensate was measured by means of a Fisher electro-photometer. Sodium chloride was used as a tracer, being present in the

feed solution at a concentration of 0.5 g/l. Any chloride in the condensate was precipitated as silver chloride by means of silver nitrate, and the degree of contamination was measured as a function of light transmission through the resulting turbid solution. The electrophotometer was calibrated using standard solutions of sodium chloride which had been precipitated with silver nitrate in nitric acid solution.

CONCLUSIONS

1. No noticeable sodium nitrate crystallization appeared on the surface of the evaporator.
2. Heat transfer coefficients for the liquid film could not be correlated as a function of liquid flow rate, temperature, and solution concentration due to poor precision in the data; however, an average value of 1225 Btu/(hr)(sq ft)(F) can be assumed.
3. Entrainment is believed due to faulty operating conditions and not due to the mechanism of evaporation.
4. By virtue of the above conclusions falling film evaporators will successfully concentrate the waste solutions encountered at X-10 if satisfactory decontamination can be achieved at higher evaporation rates.

RECOMMENDATIONS

It is recommended that:

1. More extensive and precise data be taken so that heat transfer coefficients may be determined as a function of peripheral flow rate, temperature difference, and solution concentration.
2. A small surge tank be placed at the top of the existing feed standpipe.
3. The heating capacity of the feed preheater be greatly reduced.
4. The existing leaks in the equipment be repaired.
5. A steam jacket be built for the existing evaporator.

LOCATION OF ORIGINAL DATA

The original data are located in Data Book 1075 on pp. 72 through 76, and in Data Book 1299 on pp. 47 through 62.

H. C. Harrison

P. J. Hess

H. T. Tupper

APPENDIX

A. Sample Calculations

The sample calculations were based on Run 10, which was considered a typical run.

Determination of Heat-transfer Coefficients:

$$Q = hA\Delta T$$

or

$$h = \frac{Q}{A \Delta T}$$

where h = heat transfer coefficient, Btu/(hr)(sq ft)(F)
 Q = heat transferred, /hr
 A = heat-transfer area, 2.165 sq ft
 ΔT = temperature driving force, F

Determination of Q :

$$Q = W_e h_{fg} \left(\frac{60}{\theta}\right)$$

where θ = duration of run, 6 min
 W_e = weight of condensate in time θ , 1.47 lb
 h_{fg} = heat of vaporization of water in film temperature, 968 Btu/lb

$$\begin{aligned} Q &= (1.47)(968)\left(\frac{60}{6}\right) \\ &= 14,230 \text{ Btu/hr} \end{aligned}$$

Determination of ΔT :

$$\Delta T = T_w - t_f$$

where T_w = wall temperature
 t_f = temperature of falling liquid layer

The average wall temperature was based on weighting the four center temperatures as one each and the two end temperatures as one-half each. For Run 10 the temperatures measured, from top to bottom were: 217, 220, 222,

221, 217 F.

$$T_w = \frac{\frac{217}{2} + 220 + 222 + 222 + 221 + \frac{217}{2}}{5} = 220.4 \text{ F}$$

The average temperature of the falling liquid layer was taken as the average of the six vapor stream temperatures.

$$t_f = \frac{214 + 215 + 216 + 216 + 214 + 215}{6} = 215.0 \text{ F}$$

$$\begin{aligned} \Delta T &= 220.4 - 215.0 \\ &= 5.4 \end{aligned}$$

$$\begin{aligned} h &= \frac{Q}{A \Delta T} \\ &= \frac{14,230}{(2.165)(5.4)} \\ &= 1,218 \text{ Btu/(hr)(sq. ft)(F)} \end{aligned}$$

Determination of Condensate Contamination:

$$C = \frac{K(W)(R)(100)}{(k)(D)}$$

where C = condensate contamination, wt % NaNO_3
W = concentration of NaCl indicated by turbidity, g/l
D = dilution of original sample, 0.80
R = ratio of pounds of NaNO_3 to grams of NaCl in feed
K = liters per gallon, 3.78
k = pounds H_2O per gallon, 8.30

For Run 10,

$$\begin{aligned} W &= 0.0002 \text{ g/l} \\ R &= \frac{35}{94} = 0.372 \text{ lb } \text{NaNO}_3/\text{g NaCl} \\ C &= \frac{(0.0002)(0.372)(3.78)(100)}{(8.30)(0.80)} \\ &= 0.004 \% \text{ NaNO}_3 \end{aligned}$$

B. Evaluation of Data

Discussion of Accuracy:

Accuracy of heat-transfer coefficients:

The accuracy of the heat transfer coefficients naturally depended on the choice of ΔT , A , and Q . Two points were involved in the choice of ΔT : the assumption that the vapor stream temperature was the same as the film temperature, and that in the tube wall the two end temperatures should be weighted only half as much as the four center temperatures. The latter assumption was based on considerations of the wall area represented by each temperature and of the end effects involved.

When calculating A it was assumed that the effective area for heat-transfer was the area of the tube heated by the resistance coils. This did not account for 5-1/2 in. of tube at the top corresponding to the weir, and the 1-1/2 in. of tube at the bottom.

Two assumptions were made when Q was calculated: that the latent heat of vaporization was taken as that of water at a saturation temperature equal to the film temperature, and that the feed entered the column at its boiling point. The final heat transfer coefficient is insensitive to either of the aforementioned assumptions.

Accuracy of entrainment measurements:

The analysis for the amount of chloride present in the condensate was undoubtedly accurate. However, the mechanism of chloride entering the condensate was uncertain in most cases. It was believed that a great deal of the entrainment found in the condensate was due to vigorous splashing in the top calming section carrying part of the feed solution up into the condensate lines. This splashing was caused by slugs of steam emitted from the feed preheater before equilibrium conditions were obtained. Consequently, the high entrainment values are probably not indicative of the entrainment actually resulting from the process of evaporation.

Precision Analysis:

Precision of heat transfer coefficients:

All measurements of time and area were considered very precise. The maximum error in reading the potentiometer was one scale division which, for the thermocouples used, was 1/3 F. However, an additional error was introduced in reading wall temperatures due to their continued oscillation. This was estimated to be 1/2 F. Therefore, the maximum error in reading wall temperatures was 1/3 F plus 1/2 F, or 5/6 F, while the maximum error in reading vapor temperatures was 1/3 F. Condensate weights were precise to 1 g. Concentrate weights, weighed on Toledo scales, were precise to 0.1 lb.

$$Q = W_e h_{fg} \left(\frac{60}{\theta} \right)$$

where $\theta = 6.00 \text{ min}$
 $h_{fg} = (968 \pm 0.05\%) \text{ Btu/lb}$
 $W_e = 1.47 \text{ lb} \pm 1 \text{ g}$
 $= (1.47 \pm 0.15\%) \text{ lb}$

$$Q = (1.47 \pm 0.15\%) (968 \pm 0.05\%) \left(\frac{60.0}{6.00} \right)$$

$$= (14,230 \pm 0.20\%) \text{ Btu/hr}$$

$$\Delta T = T_w - t_f$$

where $T_w = (220.4 \pm 0.83) \text{ F}$
 $t_f = (215.0 \pm 0.33) \text{ F}$

$$\Delta T = (220.4 \pm 0.83) - (215.0 \pm 0.33)$$

$$= (5.4 \pm 1.16) \text{ F}$$

$$= (5.4 \pm 21.5\%) \text{ F}$$

$$h = \frac{Q}{A \Delta T}$$

$$= \frac{(14,230 \pm 0.20\%)}{(2.165)(5.4 \pm 21.5\%)}$$

$$= (1,218 \pm 21.7\%) \text{ Btu/(hr)(sq ft)(F)}$$

Precision of entrainment calculations:

$$C = \frac{(K)(W)(R)(100)}{(k)(D)}$$

where $D = \frac{20.00 \pm 0.01}{25.00 \pm 0.01}$
 $= \frac{20.00 \pm 0.05\%}{25.00 \pm 0.04\%}$
 $= 0.80 \pm 0.09\%$

$$W = 0.0002 \pm 0.00005$$

$$= 0.0002 \pm 25\%$$

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C. Summary of Data and Calculated Values

Table AI

Run No.	Concentration (wt of NaNO ₃ per 100 wt of H ₂ O)	Flow Rate (lb/min)	Peripheral Flow lb/(hr)(ft)	Evaporation Rate (lb/min)	Reserve Temp (F)	Falling Film Temp (F)	Wall Temp (F)	ΔT (F)	Heat Input (Btu/hr)	Heat Trans to Fluid (Btu/hr)	Heat Trans Coefficient Btu/(hr) (sq ft) (F)	NaNO ₃ in Cond. (wt %)
1	2.00	1.483	164.5	0.268	203	211.0	217.0	6.0	17,200	15,600	1200	0.000
2	2.00	1.546	171.4	0.401	204	211.3	219.5	8.2	27,000	23,400	1320	0.000
3	2.00	1.209	134.1	0.526	205	211.0	224.0	13.0	34,200	30,600	1086	0.000
4	8.43	1.48	164.1	0.250	202	216.3	222.0	5.7	16,800	14,520	1180	0.015
5	8.43	1.537	170.4	0.392	202	215.2	224.0	8.8	26,200	22,750	1190	0.013
6	8.43	1.40	155.3	0.504	202	215.0	226.0	11.0	33,300	29,200	1230	0.008
7	8.43	6.40	709.8	0.491	202.5	214.3	225.5	11.2	33,750	28,500	1175	0.004
8	8.43	6.35	704.2	0.378	202	214.2	222.0	7.8	26,200	21,950	1300	0.002
9	8.43	6.39	708.7	0.241	202.5	214.2	220.0	5.8	16,700	14,050	1120	0.004
10	8.43	2.93	324.9	0.245	202	215.0	220.4	5.4	16,800	14,230	1218	0.004
11	8.43	2.89	320.5	0.390	202	214.0	221.8	7.8	26,400	22,700	1344	0.000
12	8.43	2.90	321.6	0.500	202	213.2	222.2	9.0	33,600	29,000	1490	0.004
13	8.43	2.85	316.1	0.627	204	211.8	224.0	12.2	42,000	36,500	1380	0.003
14	2.00	6.60	731.9	0.242	202	208.8	214.1	5.3	17,130	14,100	1230	0.021
15	50.00	1.547	171.6	0.227	206	225.5	231.4	5.9	16,620	13,100	1024	0.175
16	50.00	1.49	165.2	0.370	202	225.5	233.7	8.2	26,000	21,200	1193	0.025
17	50.00	3.19	353.8	0.363	209	224.0	234.3	10.3	26,250	21,000	938	0.000
18	50.00	3.16	350.4	0.242	207	222.5	229.5	7.0	17,200	14,000	924	0.050
19	50.00	6.41	710.9	0.390	211	223.5	232.0	8.5	26,800	22,550	1223	0.000
20	50.00	6.39	708.7	0.513	211	223.3	233.7	10.4	34,200	29,600	1315	0.025
21	50.00	6.34	703.1	0.263	211	223.0	229.3	6.3	16,900	15,230	1118	0.038
22	25.00	2.805	311.1	0.222	198	217.5	222.9	5.4	16,700	12,840	1100	0.050
23	25.00	2.78	308.3	0.390	206	217.5	224.7	7.1	26,200	22,600	1470	0.050
24	25.00	2.89	320.5	0.502	205	217.3	226.9	9.6	33,900	29,100	1400	0.000
25	25.00	1.534	170.1	0.502	204	217.5	228.9	11.4	33,850	29,100	1180	0.025
26	25.00	1.60	177.4	0.373	197	215.5	225.9	10.4	26,050	21,650	962	0.025
27	25.00	1.52	168.6	0.245	198	216.2	222.7	6.5	17,080	14,300	1015	0.000
28	25.00	8.85	981.5	0.208	203	215.2	218.8	3.6	17,150	12,400	1590	0.050
29	25.00	6.06	672.1	0.202	200	215.0	219.8	4.8	16,800	11,700	1124	0.025
30	25.00	6.14	680.9	0.332	200	213.2	221.8	8.6	26,000	21,350	1145	0.025
31	25.00	5.25	582.2	0.503	207	217.0	226.9	9.9	33,900	29,200	1360	0.025

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$$\begin{aligned}
 R &= \frac{35 \pm 0.25}{94 \pm 0.10} \\
 &= \frac{35 \pm 0.71\%}{94 \pm 0.11\%} \\
 &= 0.372 \pm 0.82\%
 \end{aligned}$$

k, K, and 100 may be considered exact

$$\begin{aligned}
 C &= \frac{(3.78)(0.0002 \pm 25\%)(0.372 \pm 0.82\%)(100)}{(8.30)(0.80 \pm 0.09\%)} \\
 &= 0.00423 \pm 25.9\% \\
 &= (0.004 \pm 0.001) \text{ wt } \% \text{ NaNO}_3
 \end{aligned}$$

D. Literature Citations

1. Chapman, A. I., Griffith, W. L., and Jasny, G. R., "Design and Construction of Falling Film Evaporator", M.I.T. Practice School Report, EPS-K85, Oak Ridge (1950).
2. McAdams, W. H., "Heat Transmission", p 203, New York, McGraw-Hill Book Company, Inc. (1942).

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