Entrainment from a Submerged Combustion Evaporator

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Entrainment from a submerged combustion evaporator system was studied with sodium ion as a tracer. By measuring the ratio of the sodium concentration in the pot to that in the condensate the entrainment removal performance of the evaporator system was studied under various conditions. It was observed that the log of the concentration ratio decreases with an increase in the temperature of the gaseous products of combustion as they emanate from the combustion chamber into the solution. This is attributed to the fact that a greater amount of fine ($< 5\ \mu$) droplets of entrainment are formed in the evaporator as the temperature of the gases increases.

Submerged combustion can be described as the burning of a gaseous fuel in a burner completely immersed in a liquid. Burners of this type are used to heat, evaporate, or carbonate solutions. As an evaporator the heat released within the body of a liquid by the burning gases is transferred via two paths: by direct contact of the hot gaseous products of combustion with the liquid for a short period, and to a lesser degree through the walls of the combustion chamber. Figure 1 is a schematic diagram of how such a unit works as an evaporator. As can be seen it is similar to a welder's gas torch operating under water, where the heat released from the burning reaction is transferred from the hot gases to the liquid by direct contact as the gases sparge through the solution. This method is novel and has found many applications in industry (*2, 4, 12, 13*); however wider usage has been deterred because of high entrainment losses. Entrainment is the carry-over of liquid particles from the evaporator pot along with the rising vapor. Because of this physical phenomenon pure condensate free of solute is impossible to attain in a single-stage evaporator.

The purpose of the study presented herein was to determine the cause of excessive entrainment from submerged combustion evaporator systems.

THEORY

The mechanisms of entrainment formation have been investigated by Newitt (*10*). When a gas or vapor disengages from a liquid, droplets of liquid are always entrained in the rising gas when the velocity of the gas is greater than the terminal settling velocity of the droplets. At the disengaging surface fine droplets are formed when the liquid film of a bubble bursts. The burst occurs when the surface tension of the liquid film is overcome by the pressure within the bubble. This results in the shattering of the liquid film into small fragments which form into various size droplets, with the finer fraction generally carried along with the rising gas or vapor.

The size distribution and amount of these droplets encountered in evaporators were explored by Garner (*7*) and O'Connell (*11*) using tube evaporators. Garner's results indicate that it is possible to obtain a condensate containing only one millionth of the solute concentration of the pot (equivalent to one part entrained per million parts of vapor). This can occur when complete removal of all entrained droplets larger than approximately 5 μ is achieved.

Complete removal of entrained droplets 5 μ or larger is possible if appropriate separators are used under optimum conditions. This is suggested by the theoretical treatment of Othmer (*5*) on wire mesh entrainment separators. Optimum utilization of about 4 in. of water pressure drop in an impingement or inertial type of separator usually removes the troublesome entrainment to one part per million parts of vapor. Consequently a submerged combustion evaporator can produce condensate of high purity provided the following assumptions hold true: fine entrainment formation is solely by the bubble bursting mechanism, the entrainment droplet size distribution is similar to a tube evaporator, complete removal of droplets 5 μ and larger is accomplished prior to condensation, and solute is present in the condensate as a result of entrainment.

PREVIOUS WORK

Generally an inertial type of separator (baffle, etc.) is sufficient to reduce entrainment in evaporators to a tolerable amount. Studies on entrainment, where such separators were employed with conventional (steam tube or coil) evaporators, have been reported (*1, 5, 7*). However little information has been reported concerning entrainment from submerged combustion evaporators. Badger and Lindsay (*3*) describe entrainment from submerged combustion evaporators as a major problem. Cronan (*6*) and Weyermuller (*14*) mention the utilization of venturi scrubbers for submerged combustion evaporators to reduce the troublesome entrainment. Since the purchase of a one million B.t.u./hr. experimental submerged combustion evaporator, Krieg (*9*) and Kleinpeter (*8*) have measured how severe the problem really is. The entrainment was observed to be 100 to 1,000 times more than that experienced from conventional evaporator systems. Kleinpeter utilized a separator system consisting of a cyclone, three bubble-cap trays (operating from zero to total reflux), and a wire mesh separator, all in series. His results show that the amount of entrainment penetrating these separators was 100 fold more than for an equivalent separator system used for a coil evaporator (*1*).

The fundamental difference between submerged combustion and conventional evaporators is that the former utilizes sparging with hot gaseous combustion products. Therefore the heat is transferred mostly by direct contact of the gas phase with the solution, rather than through a metallic medium. This suggests that more than normal entrainment from submerged combustion evaporators may be caused by the mode of heat transfer and its associated variables such as gas temperature and gas velocity.

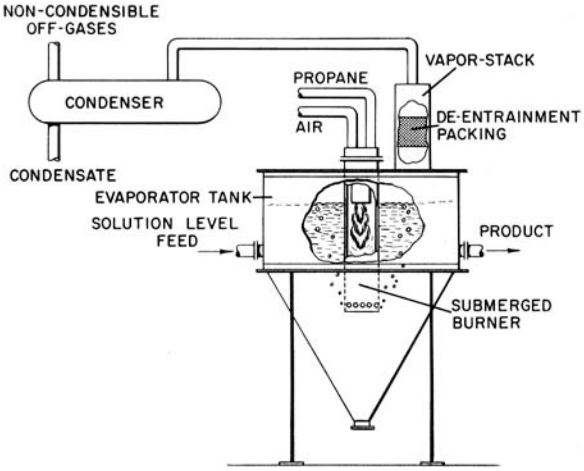

Fig. 1. Typical submerged combustion evaporator.

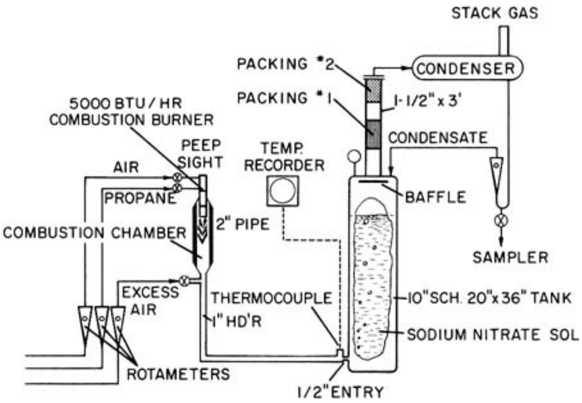

Fig. 3. Phase III equipment diagram.

EXPERIMENTAL EQUIPMENT

With published information an evaporator system was designed such that the performance of all components could be predicted. The choice of wire mesh entrainment separators operating within optimum vapor velocities is an example. Variables which had negligible effects upon entrainment were only briefly studied, while variables peculiar to submerged combustion were studied in greater detail. Observations noted during the preliminary course of investigation suggested equipment modifications in order to make further studies. Consequently the experimental work resulted in three phases, each of which was characterized by an equipment modification. The third phase was conducted, with a laboratory scale submerged combustion system, to verify a correlation of the data obtained from the larger burner of one million B.t.u./hr.

Phase I

Figure 2 is a schematic diagram of the one million B.t.u./hr. evaporator system used during the first phase of investigation. An air lift chamber with downward deflection was used to keep the flame area portion of the combustion chamber adequately cooled while varying the tank liquid level. In this way the effect of the tank freeboard could be studied. Freeboard is the height in the tank above the liquid level available for large droplets of entrainment to settle out. Atomizing sprays below each wire mesh packing were installed in order to cause partial condensation upon entrained droplets (nuclei), thereby increasing their size and facilitating their removal.

Blank plugs in the center of the pads provided vapor velocities through the pads between 5 and 10 ft./sec., an optimum range for high removal efficiencies. Pad number 1 was a standard mesh (0.011-in. diameter wire with 110 sq. ft./cu. ft. of surface area). Pad number 2 was a finer wire mesh (0.0045 in. diameter wire with 330 sq. ft./cu. ft. of surface area). Both pads were 6 in. thick and installed to provide progressive degrees of entrainment removal. Condensate was routed to a sump or recirculated.

Phase II

The submerged combustion assembly used during the second phase of study was similar to that shown in Figure 2 except for the following alterations:

1. The removal of the air lift chamber. 2. The addition of additional heat transfer surface to the combustion chamber. 3. The installation of a thermocouple at a point where the hot gas contacts the solution. 4. The addition of a third entrainment separator pad in the tower. 5. The installation of a 12-in. diameter glass observation port on the tank dome.

The air lift chamber was removed, since the effect of freeboard was found to be insignificant and further variations in the tank liquid level were not necessary.

The addition of heat transfer surface to the combustion chamber was made to provide for a greater percentage of heat dissipation via the metal walls. This was done by attaching 4-ft. lengths of ⅝-in. diameter steel tubes to the gas ports shown in Figure 2. This allowed the combustion gases to dissipate more of their heat via a metallic medium before being discharged into the solution. This resulted in lower gas exit temperatures than previously experienced for equivalent heat inputs.

The thermocouple at the point of gas-to-liquid contact was installed to measure directly the gas exit temperature. The thermocouple however proved unsatisfactory because of a thermal ground at the junction with the tube metal wall.

Pad number 3 was installed to provide an extension of the progressive degrees of entrainment removal. It was made of 0.011-in. diameter stainless steel wire spun coated with fiber glass and provided greater surface area/unit of volume than pad number 2.

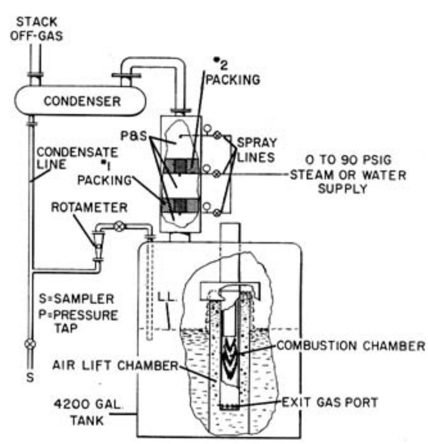

Fig. 2. Phase I equipment diagram.

Phase III

Figure 3 is a schematic of the assembly used in the final third phase of study. This was a scale down from the nominal one million B.t.u./hr. burner to a 5,000 B.t.u./hr. unit. Basic design changes were made to afford complete control of the gas exit temperature. External location of the burner and combustion chamber provided access for manual lighting of the burner. Externally fined heat exchanger surfaces in the condenser were used to minimize the condenser pressure drop. The provisions for entrainment removal were identical, in principle, to Phase I.

EXPERIMENTAL PROCEDURE

Sodium ion was used as a tracer element for all runs, since a sodium spectrometer was available capable of detecting trace amounts as small as 0.1 p.p.m. All the systems were operated approximately 6 hr. to allow equilibrium to be attained before sampling. The circulation rate of condensate to the pot was measured by a rotameter. Equilibrium was established when the condensate rate ceased to increase. The condensate was then routed to a sump or left circulating. Solutions of sodium nitrate were used in all runs except two, where a high salt solution of sodium hydroxide, nitrate, nitrite, and aluminate was used. Vapor samples at various localities in the system were obtained by passing the vapor through a small portable condenser and collecting the condensate. Samples of the pot solution were taken at the end of each run.

DISCUSSION OF RESULTS

Entrainment Removal Performance

By measuring the ratio of solute concentration in the pot to that in the condensate the entrainment removal performance of an evaporator system can be described. This ratio can vary greatly from system to system. For a nonvolatile solute, such as sodium chloride, knowledge of the entrainment removal performance for a salt evaporator system enables the prediction of the salt concentration of the condensate.

Boil Up Rate

For an evaporator of fixed diameter the boil up rate establishes the superficial vapor velocity in the vapor space of the evaporator. Entrained droplets with terminal settling velocities equal to or less than the established vapor velocity are carried along with the vapor toward the condenser.

Less than a twofold decrease in entrainment was measured when the boil up rate was decreased by one-half at constant freeboard. Furthermore the superficial vapor velocities encountered in the 8-ft., 10-in. diameter tank of Phase I and II were less than 1 ft./sec., whereas commercially designed evaporators operate at vapor velocities greater than 2 ft./sec. Consequently the effect of boil up rate on entrainment is not of sufficient order of magnitude to be considered as a major contributor.

Freeboard

No appreciable decrease in entrainment was noted when the pot freeboard was increased. The freeboard range reported in Table 1 is from 2 to 6 ft.

When the boil up rate is constant, the greater the freeboard the greater the residence time an entrained droplet has in order to settle out in the tank vapor space. Table 1 shows that no significant change in entrainment reaching the condenser can be attributed to the effects of varying the freeboard.

Foaming

Visual observations during Phase II indicated that foaming was not a problem. Splashing produced by the gas-vapor mixture breaking through the liquid surface created an area free of foam in the immediate vicinity. The splashing liquid in fact acted as a mechanical foam breaker. The foam present was only in the relatively calm areas of the liquid surface and at no time, or location, was this foam greater than 3 in.

Surface Tension

The entrainment removal performance was not improved by the addition of a surface active agent (antifoam). Although the surface tension of the solutions used was not measured, it was appreciably lowered by the addition of an antifoaming agent (Run 14). The result was an increase in entrainment as would be expected from the lowering of the surface tension of the solution.

TABLE 1. PHASE I AND II RUN SUMMARY

Run no.	Boil up rate, lb./hr.	Free-board, ft.	Pot conc., g./l Na^+	Cond. conc., p.p.m. Na^+	Entrain-ment removal perform-ance $\times 10^3$	Gas exit* velocity, lb./hr./sq. ft. $\times 10^3$	Gas exit tempera-ture, °F.†
1	715	4.2	20.8	5.3	3.93	32.0	2,120
2	1020	4.0	19.6	6.6	2.97	32.0	2,200
3	970	3.8	18.4	6.3	2.92	31.0	2,100
4	535	4.0	20.6	4.5	4.58	21.0	1,656
5	725	4.0	20.6	5.3	3.90	27.4	1,980
6	725	4.3	20.3	4.95	4.15	27.4	1,980
7	715	4.2	20.7	4.3	4.80	27.4	1,980
8	730	4.3	24.5	8.56	2.86	27.4	1,980
9	770	4.5	27.6	6.3	4.40	32.0	1,820
10	820	5.7	33.5	12.4	2.70	30.4	1,840
11	780	6.1	36.0	10.9	3.30	30.4	1,840
12	525	6.2	36.0	8.2	4.40	22.8	1,650
13	545	6.2	36.0	3.7	9.70	31.3	1,400
14	485	5.8	35.0	17.5	2.00	31.3	1,400
15	610	2.0	14.0	0.7	20.0	31.3	1,400
16	470	1.8	14.0	0.4	35.0	31.1	1,140
17	280	2.0	14.0	0.3	47.0	32.2	875
19	795	2.0	14.8	0.22	67.0	30.8	
20	585	2.0	14.8	0.1	148	30.9	
21	740	2.0	14.8	0.1	150	30.9	
22	665	2.0	15.0	0.1	150	30.1	
24	740	3.8	100	0.1	1000	29.9	
25	765	2.0	120	0.4	300	29.9	
Krieg	900	2.0	—	—	0.25	32.0	2,370
Kleinpeter	900	2.0	—	—	3.50	32.0	1,830

* Total area of gas ports equal to 4.9 sq. in.
† Calculated for Runs 1 through 17, Krieg and Kleinpeter.

Condensing Techniques for Particle Build Up

No noticeable improvement in the entrainment removal performance of the system was obtained by preconditioning the vapor-gas mixture. Several methods (sonic agglomeration, electrostatics, partial condensation) could have been used to improve the performance of the equipment. Only one of these methods was tried. Sprays utilizing hot or cold water, or steam, were used to promote partial condensation upon small entrained nuclei for the specific purpose of building them up to a size easily removed.

Gas Dispersion

The effect of port size or configuration was not studied. Gas exit ports were held nearly constant in diameter and shape. Five eighths-in. diameter holes were used throughout all phases of work.

Gas Exit Velocity

No major effect upon entrainment is attributed directly to the gas exit mass velocity. The data of Table 1 shows that for nearly identical gas velocities that there can be a considerable difference in the entrainment when the temperature of the gas is varied.

Gas Exit Temperature

The effect of the gas exit temperature is quite pronounced and appears to be the main contributor to poor entrainment removal performance. In order to reduce gas exit temperatures several methods were employed. Excess air was used in order to lower the flame temperature and consequently the resulting gas exit temperature. The limitations of the one million B.t.u./hr. burner were such that in order to provide excess air the propane rate had to be decreased. This resulted in a lower heat input but was necessary because the air compressor available could only provide 210 std. cu. ft./min. of air which was equivalent to 0% excess air at a one million B.t.u./hr. propane rate. However additional heat transfer area was added to the combustion chamber during Phase II (Runs 19 through 25). This permitted a greater portion of the heat input rate to transfer through the metal walls. The result was a lower gas exit temperature, for an equivalent rate of heat input, than in Phase I. This was not enough to achieve the low temperature desired, and consequently some excess air was also used during Phase II.

Upon the completion of twenty-five runs the data was assembled and estimates made of the gas exit temperatures. The estimates are tabulated in Table 1. A plot of the entrainment re-

TABLE 2. PHASE III RUN SUMMARY

Run no.	Pot conc., g./l Na^+	Condensate conc., p.p.m. Na^+	Entrainment removal performance $\times 10^3$	Gas exit, temperature, °F.*
26	45.0	0.70	64.20	886
27	55.0	0.30	183	680
28	60.0	2.0	30	1,122
29	66.0	1.0	66	1,372
30	66.0	0.5	132	886

* Measured directly.

moval performance vs. gas exit temperature, Figure 4, was based on the above data. Verification of the above results was made during Phase III where the temperature was measured with a high temperature gas thermocouple installed in the hot gas stream prior to its injection into the solution. The results are shown in Table 2 and also Figure 4.

General Observations

During the course of the experimental work several observations were made which are pertinent to the overall problem. An assembly of pictures were taken of the noncondensibles issuing from the condenser used during Phase III, under conditions of different gas exit temperatures. The degree of cloudiness of the noncondensibles was observed to be proportional to the entrainment. This observation and the experience gained during Phase II led to predictions of the entrainment removal performance factors prior to receiving laboratory analysis of samples taken during Phase III. The predictions were surprisingly accurate.

Although the pictures could be duplicated with a high salt solution, they were taken while boiling tap water. It is anticipated they can be duplicated with distilled water. The significance of this is that the entrained particles are liquid in nature, at least for the temperatures at which the pictures were taken.

Since the droplet-size distribution of entrainment from submerged combustion evaporators is of great importance, it can be said that at high gas temperatures a portion of the droplets must be submicron in size. This statement can be made from the observation that the droplets contributing to the cloudiness of the noncondensible off-gas stream were not completely removed by a series of entrainment separators even when passed through a condenser.

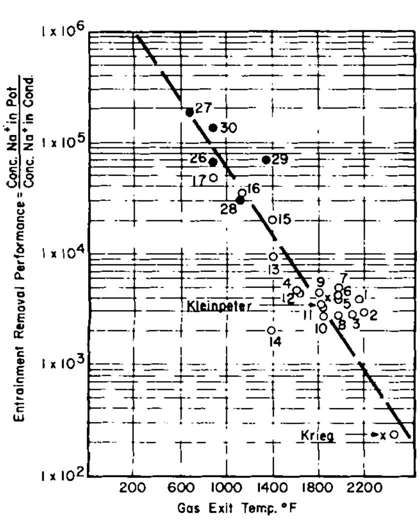

Fig. 4. Entrainment-removal performance vs. gas exit temperature, °F.

SUMMARY AND CONCLUSIONS

The quantities of gases and vapors produced in the submerged combustion evaporator per unit of liquid surface area were not excessive. When one assumes a normal droplet-size distribution, inertial separators in series should have accomplished adequate entrainment removal but did not. It was found when a series of separators was used that the entrainment removal performance was not comparable to the performance normally encountered in other types of evaporators employing similar separators. Therefore the amount of entrained droplets less than 5 μ is much greater than for conventional evaporators.

The gas exit temperature was found to be related to the entrainment removal performance as shown in Figure 4. The penetration of entrainment through the separators (some passed the condenser also) shows that they are mostly less than 5 μ in size, with submicron droplets also present. The amount of these droplets increases as the temperature of the gaseous combustion products (at the point of gas to liquid contact) increases.

Since the amount of fine droplet formation by the mechanism of bubble bursting at a liquid surface is considerably less than that experienced in the submerged combustion evaporator, it is concluded that the additional fine droplets encountered originate below the liquid level.

The mechanism of formation of these additional droplets can only be theorized. The high gas exit temperatures used in submerged combustion evaporators in conjunction with high gas exit velocities probably produce a series of events at the instant the gas contacts the liquid. The events are: coarse droplet entrainment, from flashing and/or high gas velocity atomization of the liquid, and reduction in size, by evaporation, of the entrained droplets in the gas phase to less than 5 μ. Once formed these fine droplets within a gas bubble are physically stable and will not be removed while the bubbles of gas pass up through the liquid nor by low pressure drop impingement type of separators. When high entrainment removal is required for a submerged combustion evaporator system, the gas exit temperature should be considered.

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LITERATURE CITED

1. *Atomic Energy Commission Research and Development Report* BNL-59 (March 27, 28, 1950).
2. Anderson, C. O., and E. W. Douglass, *Chem. Met. Eng.*, **48**, 135 (May, 1941).
3. Badger, W. L., and R. A. Lindsay, *Ind. Eng. Chem.* **49**, No. 3, Part 1 (1956).
4. Batholomew, F. J., *Chem. Eng.*, **57**, 118 (Aug., 1950).
5. Carpenter, C. L., and D. F. Othmer, *A.I.Ch.E. Journal*, **1**, No. 4, p. 549 (December, 1955).
6. Cronan, C. S., *Chem. Eng.*, **63**, No. 2, (February, 1956).
7. Garner, F. H., et al., *Trans. Inst. Chem. Engrs.* (*London*), 32, 222 (1954).
8. Kleinpeter, J. H., "General Electric Company Notebook," Unpublished (1955).
9. Krieg, J. T., "General Electric Company Memos," Unpublished (1954).
10. Newitt, D. M., et al., *Trans. Inst. Chem. Engrs.* (*London*), **32**, 244 (1954).
11. O'Connell, H. E., and F. S. Pettyjohn, *Trans. Am. Inst. Chem. Engrs.*, **42**, p. 795 (1946).
12. Weisman, W. I., *Chem. Eng. News*, 33, 2329 (May, 1955).
13. ———, *Chem. Eng.*, **57**, 169 (Nov., 1950).
14. Weyermuller, G., and J. Goodson, *Chem. Processing*, **2**, 116 (Oct., 1956).

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