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TWELFTH QUARTERLY PROGRESS REPORT

on

THE DEVELOPMENT OF ADVANCE-BASE THERMOCOMPRESSION SEA-WATER STILLS

to

U. S. NAVAL CIVIL ENGINEERING
RESEARCH AND EVALUATION LABORATORY
PORT HUENEME, CALIFORNIA

February 28, 1957

by

D. L. Hyatt, F. W. Fink, and J. A. Eibling

Project Noy-73219

20060302001

Battelle Memorial Institute

505 KING AVENUE COLUMBUS 1, OHIO

April 23, 1957

Officer in Charge
U. S. Naval Civil Engineering
Research and Evaluation Laboratory
Port Hueneme, California

Attention Commander C. J. Merdinger, CEC, USN

Dear Sir:

Sea-Water Distillation Project Noy-73219

Enclosed are 30 copies of our Twelfth Quarterly Progress Report on "The Development of Advance-Base Thermocompression Sea-Water Stills". The report covers the period December 1, 1956 to February 28, 1957.

The results obtained during the past month with dropwise condensation in the laboratory evaporator using Teflon-coated tubes are most encouraging. Condensation-film coefficients two to three times those obtained previously with untreated tubes have been obtained. When this improvement is combined with the increase in boiling-film coefficient obtainable with forced-convection evaporation, gains in the over-all rates of heat transfer of 40 to 130 per cent are effected. Thus, by incorporating these changes in the design of an evaporator, much less heat-transfer surface is required. Or as an alternative, if the heat-transfer surface is held the same as that in conventional evaporators, the increase in heat-transfer rate can be used to improve the operating economy of the still. In the latter instance, however, it appears that only the gain effected by dropwise condensation can be used to improve the operating economy. The portion of the potential gain in still performance resulting from forced convection is, according to our studies, offset by the additional power required for circulating the water.

Inasmuch as the research program ends in March, we have started the preparation of a summary report which will be mailed to you in April. The summary report will cover all of the work performed since November, 1955, and will include our recommendations for the design of an improved prototype evaporator based on the data so far obtained.

Time did not permit investigating several areas of potential improvement. We urge that this work be continued, as the possibilities for further improvement of the evaporator appear attractive. Accordingly we shall outline in the summary report, for your consideration, a recommended program for continuing the study. Also we plan to leave the laboratory equipment assembled for some time so that it could be used with minimum setup time if further work is decided upon.

As usual we would welcome your comments or questions concerning this research program.

Yours very truly,

James A. Eibling

James A. Eibling

JAE:rh

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on

THE DEVELOPMENT OF ADVANCE-BASE THERMOCOMPRESSION SEA-WATER STILLS

by

D. L. Hyatt, F. W. Fink, and J. A. Eibling

INTRODUCTION

This is the twelfth quarterly progress report on the development of advance-base thermocompression sea-water stills. The report covers the period December 1, 1956, to February 28, 1957. During this period tests were conducted with a laboratory evaporator using dropwise condensation and forced-convection evaporation. The purpose of the tests was to determine quantitatively the improvement in heat transfer that can be made under these conditions of operation. Also, considerable time was spent in attempting to run the experimental evaporator under natural-convection operation. These attempts were not successful for reasons given in the report.

In addition to reporting on this work, a section of the report presents information obtained in a survey of the suitability of various materials of construction for sea-water evaporators and heat exchangers.

SUMMARY

The results of experiments with dropwise condensation and forced-convection evaporation are presented in this report in curve form. The results cover a range of over-all temperature differences between condensing steam and evaporating water of 2 to 18 F with forced convection flow velocities of 3, 6, and 10 fps. Dropwise condensation was promoted on the evaporator tubes with a Teflon film approximately one-half mil thick. Teflon has a particularly desirable feature in this application in that it presents a permanent dropwise promoting surface; other materials that have been tried, such as certain oils or mercaptans, wash away and must be continually replaced. The Teflon film, of course, offers some resistance to heat flow. However, the net effect is to increase the heat transfer significantly. For example, at a condensing film temperature difference of 2 F, tests showed that the heat flux was twice as much for dropwise condensation as for film-type condensation. The value increases to three times as much at a temperature difference of 1 F. This increase in condensing-film coefficient effects a 10 to 39 per cent improvement in the over-all heat-transfer rate, depending on the flow velocity and over-all temperature difference used. The greatest gain occurs with an over-all Δt of 4 F and a flow velocity of 6 fps; this combination yields a 39 per cent increase over film condensation at the same Δt and flow rate.

A section of this report presents a summary of material obtained in a survey of the corrosion resistance of commercially available alloys that might be used in the fabrication of thermocompression stills. The results of the survey point out the fact that there are few data on sea-water corrosion at the temperature and velocities encountered in thermocompression stills. Based on present knowledge and experience, a 70-30 cupro-nickel alloy is recommended for the tubes in the evaporator and in the several heat exchangers of a still. Considerable research would be required to demonstrate the practicality and economy of an all-aluminum design. The suggestion is made of the long-range possibility of using solid titanium or titanium-coated tubes for evaporators. Titanium is essentially immune to attack by sea water. Moreover, there is evidence that titanium presents a surface which, to some degree, induces dropwise condensation without any additional promoting agent.

RESULTS OF HEAT-TRANSFER TESTS

Heat-transfer coefficients were obtained in a three-tube laboratory still over a range of over-all temperature differences of 3 to 18 F with dropwise condensation outside the evaporator tubes, and with forced-convection evaporation inside the tubes for flow velocities of 3, 6, and 10 fps. The dropwise condensation was promoted with a Teflon film, estimated to be 0.0005 in. thick. The film was applied by spraying Du Pont's Teflon one-coat enamel No. 851-204 on the tubes and curing the enamel at 690 F for 1-1/2 min in a hot-air furnace.

Concurrently with these tests the pressure drop between the inlet and outlet of the evaporator tubes was measured at several flow rates and with various rates of boiling. These data will be valuable in determining the pump power requirements for a forced-convection evaporator.

Over-All Heat-Transfer Coefficients

Figure 1 is a plot of the experimentally determined heat-transfer data showing the heat flux as a function of the temperature difference between condensing steam and evaporating water, and also of the evaporating water velocity. All of the data were obtained with dropwise condensation. The curves in Figure 1 indicate an improvement of 10 to 39 per cent over the values obtained from previous tests with film-type condensation which were reported in the Eleventh Quarterly Progress Report, dated November 30, 1956. The improvement in heat transfer is due to the better film coefficient associated with dropwise condensation as compared to film-type condensation.

In carrying out the test program, two sets of test runs were made. The heat flux measured in the first set of tests was lower than that expected with dropwise condensation. In an effort to find the cause of the low coefficients, a borescope was used to inspect the nature of the condensation. This disclosed that effective dropwise condensation was occurring. Accordingly the next step was to disassemble the evaporator and inspect the boiling side of the tubes. An accumulation of scale approximately 0.003-in. thick was found on the upper two-thirds of the tube surface. Based on the difference in

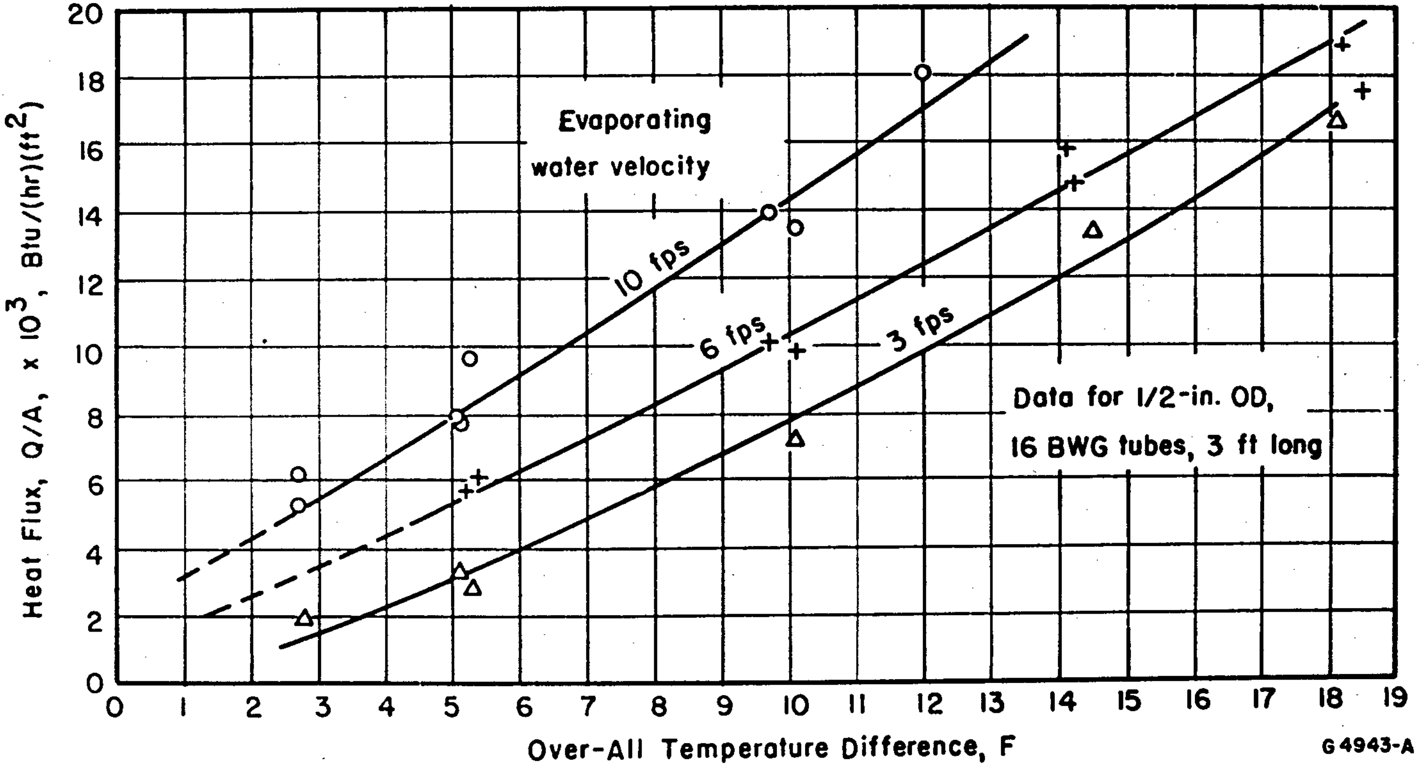

FIGURE 1. EFFECT OF TEMPERATURE DIFFERENCE AND WATER VELOCITY ON THE OVER-ALL HEAT-TRANSFER RATE, DROPWISE CONDENSATION

heat-transfer rates before and after the scale was removed, the scale had an approximate coefficient of 3000 Btu/in.(ft^2)(F). The curves of Figure 1 are based on the second set of tests, that is, the tests conducted after the scale was removed.

Condensing and Evaporating Coefficients

Figures 2 and 3 show the condensing- and evaporating-film heat fluxes plotted against the film temperature difference. These data were computed on the basis of the test data shown in Figure 1. Three condensing curves are shown in Figure 2. The upper curve is for dropwise condensation. The middle curve is based on tests performed earlier in the research program for film-type condensation, and the bottom curve is plotted from values obtained with the theoretical Nusselt equation for film condensation. The latter two curves are presented to show the improvement obtained with dropwise condensation. The film temperature difference for the dropwise condensing curve includes, in addition to the temperature drop across the condensing film, the temperature drop across the Teflon coating. Thus, the resistance to heat transfer of the Teflon coating is included in the curve for dropwise condensation. It is also included in the curves of Figure 1.

Pressure Drop at Forced-Convection Flow

Table 1 gives the pressure drop through the evaporator tubes that was obtained in tests at the various flow velocities and heat-transfer rates. From these data the forced-convection pressure drop in the evaporator of a thermocompression still can be predicted. This will be done in the optimized evaporator design, which will be presented in the summary report.

TABLE 1. PRESSURE DROP THROUGH 1/2-in. OD, 16-BWG EVAPORATOR TUBES FOR 3, 6, AND 10 FPS VELOCITIES AT VARIOUS OVER-ALL TEMPERATURE DIFFERENCES BETWEEN CONDENSING STEAM AND BOILING WATER

Forced Convection Velocity, fps	Over-All Δt, F	Pressure Drop, in. Hg
10.0	2.7	7.16
10.0	5.2	7.07
10.0	5.1	7.24
10.0	5.3	7.03
10.0	10.1	7.11
10.0	9.7	7.14
10.0	12.0	7.34
6.0	5.2	2.49
6.0	5.4	2.54
6.0	10.1	3.19
6.0	9.7	3.06
6.0	14.2	3.99
6.0	18.5	4.46
6.0	18.2	4.80
3.0	2.8	1.19
3.0	5.3	1.22
3.0	5.1	1.25
3.0	10.1	1.73
3.0	14.5	2.03
3.0	18.1	2.35

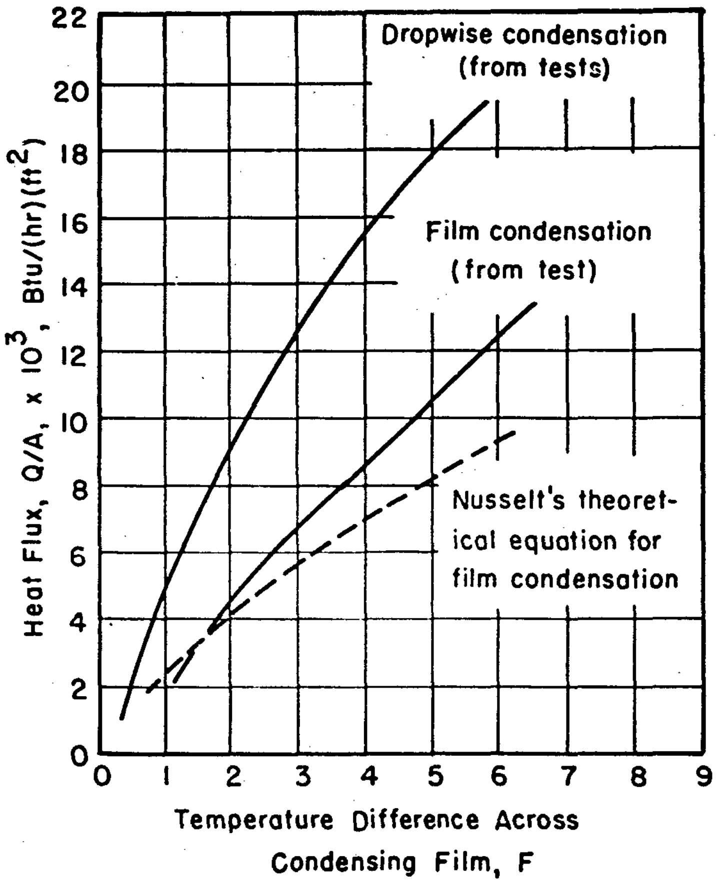

FIGURE 2. HEAT FLUX VERSUS CONDENSING-FILM TEMPERATURE DIFFERENCE

Computed on basis of Figure 1.

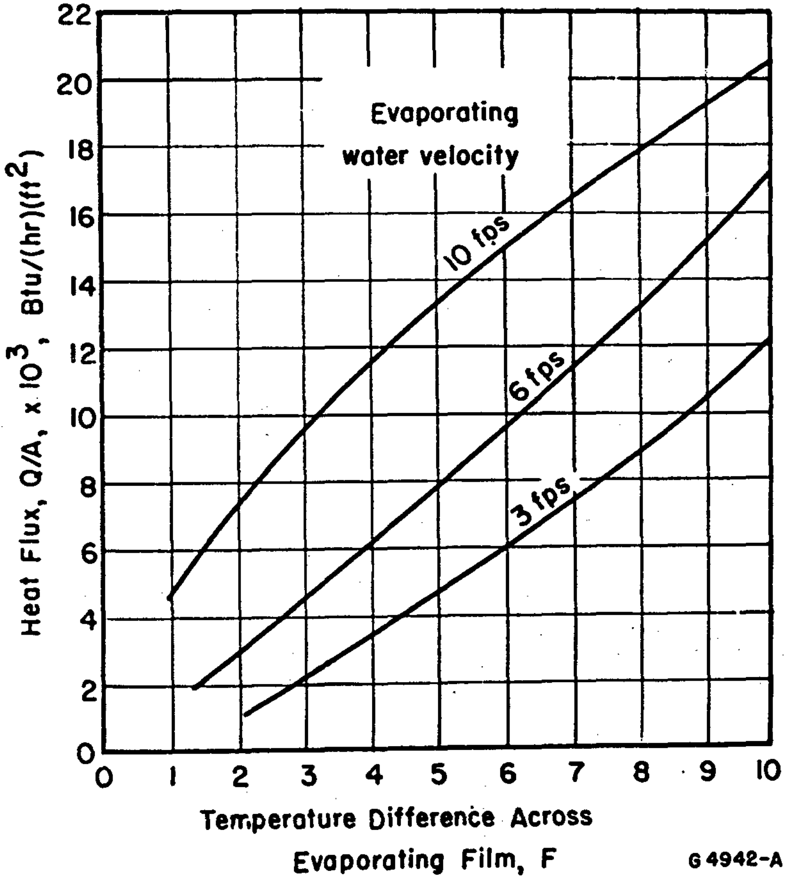

FIGURE 3. HEAT FLUX VERSUS EVAPORATING-FILM TEMPERATURE DIFFERENCE

Computed on basis of Figure 1.

Natural-Convection Evaporation

In connection with efforts to obtain data on natural-convection heat-transfer rates, the experimental apparatus was modified in such a manner that the static water level in the evaporator tubes could be varied over the height of the tubes. To accomplish this it was also necessary to throttle the circulating pump such that the static head developed, exactly equalled the friction losses in the piping external to the evaporator. The natural convection experiments were not successful partly because the pump capacity was too small at the low discharge heads required. It was also found that the balance between the water level in the tubes and the flow rate of the evaporating water was extremely critical and hence difficult to control. Moreover, the water level in the tubes increased when the evaporating water temperature increased. Also the heat flux rose with an increase in water level, which, of course, led to unsteady operation.

It is believed that with further endeavor the general methods used to simulate natural convection will be workable, and that it has the advantage that the evaporating water flow rates can be more easily and accurately measured than if a full-size natural convection evaporator with internal downcomer were used. To simulate natural convection in the laboratory evaporator, a pump with high-capacity low-head characteristics, such as an axial flow pump, would be necessary. In addition, a means for precise control of the water temperature at the inlet to the evaporator would be required.

REVIEW OF MATERIALS FOR SEA-WATER EVAPORATORS AND HEAT EXCHANGERS

Sea water, with its high chloride ion content, is corrosive to a great variety of metals. Unprotected mild steel, for example, when completely immersed in clean sea water may experience localized pitting at a rate of, say, 20 mils per year. The average penetration, however, based on loss in weight may be of the order of seven mils per year. The rate of attack for steel, as with many other metals, can be expected to increase rapidly as the temperature is elevated. As the temperature is increased beyond about 120 F, the number of available metals with good corrosion properties becomes greatly reduced. In addition to temperature, the rate of flow of the sea water also affects the rate of corrosion.

Corrosion Resistance of Various Materials

The choice of metals for service in sea water at elevated temperatures, that is, up to 350 F, is, according to some experiments performed at the U. S. Naval Experiment Station, restricted to such materials as titanium, Hastelloy C (55 Ni, 17 Mo, 16 Cr, 6 Fe, 4 W), Inconel X (73 Ni, 15 Cr, 7 Fe, 2.4 Ti), and certain stainless alloys. With regard to thermocompression stills, the selection is somewhat greater, since the maximum temperature is 220 F.

Table 2 presents the results of corrosion tests of alloys noted for sea-water resistance. Undoubtedly, there are a few other test results available in the technical literature; however, it is safe to conclude that there is a paucity of information on the corrosive behavior of materials in hot sea water. Most of the test results are based on immersion in sea water at ordinary temperatures.

Where a material is in contact with sea water, an alloy of copper, rather than, say, tough-pitch copper, normally would be chosen from the corrosion viewpoint. For velocities of flow in the range of 2 to 6 ft per sec, aluminum brass (76 Cu, 22 Zn, 2 Al) is a good choice. For higher velocities, one of the cupro-nickels normally is found to be more suitable. An alloy containing 70 Cu, 30 Ni, 0.7 Fe is resistant to corrosion at high rates of flow. A less expensive alloy containing 89 Cu, 10 Ni, 1 Fe is considered almost as resistant at ordinary sea-water temperatures.

Bimetallic tubes are available from several manufacturers. Thus it is possible to specify a copper-base alloy, such as 70 Cu – 30 Ni on the inside of the tube and say aluminum on the other side. This should be a good combination for the evaporator tubes of a thermocompression still since the inside surfaces will be in contact with sea water, and the outside with water or steam containing 17 ppm salinity. Provided no heavy metals are dissolved in the steam condensate, aluminum can be expected to give good service. Bimetallic tubes, of course, cost appreciably more than single-metal construction.

Solid 70 Cu – 30 Ni tubes should give good service. As indicated in Table 2, at 350 F the cupro-nickel alloy tends to show localized corrosion. At 220 F, there would be less tendency for this type of attack to take place.

Of the nickel-base alloys, Monel would be most likely to give good service at 220 F. A heavy corrosion scale is found on Monel after exposure at 350 F but, at 220 F, there would be less tendency for this to occur. Data are needed for both cupro-nickel and Monel at 220 F.

Of the stainless steels, those containing molybdenum are the most resistant to pitting attack in sea water. However, even the molybdenum stainless steels, such as 316 SS or Carpenter 20 are found to be rapidly attacked at local spots, e.g., under fouling or scale deposits. In Table 2, Type 316 SS showed good over-all performance, but there was local contact corrosion under the washers, where the test specimens were fastened to the fixture. Stainless steels with molybdenum have the advantage that they are much more resistant to general attack by high-temperature sea and fresh water and steam, than the copper or nickel-base alloys discussed above. Conditions must be controlled carefully to prevent fouling and local deposits if stainless steels are used.

Aluminum and certain aluminum alloys, such as those containing magnesium or silicon, have given reasonably good life in sea water at ordinary temperatures. No data for aluminum in hot sea water have been found in the literature search. It is not expected that aluminum would give good service in heated sea water, since it is inferior to copper and its alloys in sea water at normal temperatures.

TABLE 2. THE RESISTANCE OF SELECTED MATERIALS TO CORROSION BY SEA WATER

Material	Corrosion rate, in./yr, From Weight Loss				Recommended Maximum Velocity of Sea Water, ft/sec	Remarks on Test C
	Test A (360 days at 70 F)	Test B (130 days at 70 F)	Test C (30 days at 350 F)	Test D (54 days at 325 F)		
Copper	0.0016	0.0011			3	
Red brass 85 Cu-15 Zn	0.0018	0.0013				
Admiralty (70 Cu-29 Zn-1 Sn)	0.0018	0.0012			3	
Aluminum brass (76 Cu-22 Zn-2 Al)	0.0008				7	
70-30 Cupro-nickel (0.7% Fe)	0.0003	0.0010	0.019	0.0006	15	Localized corrosion
90-10 Cupro-nickel (1.7% Fe)			0.121	0.0015	15	Heavy corrosion scale
Monel (67 Ni-30 Cu-1.4 Fe)			$0.031^{(a)}$			Heavy corrosion scale
304 SS (18 Cr-8 Ni)			0.103			Severe corrosion
316 SS (18 Cr-8 Ni-2.5 Mo)			0.00005			Slight contact corrosion
Titanium			$G^{(a,b)}$			Stains at fixture contact

Test A Field test, one year in clean sea water at normal temperatures at 2-3 ft/sec, Kure Beach, N. C. Ref: "The Corrosion Resistance Characteristics of Copper and Nickel Alloys", H. O. Teeple, International Nickel Co., Inc., New York 5, N. Y.

Test B Field test, 130 days in Galveston Bay at a velocity of 1-2 ft/sec. Ref: Same as for Test A.

Test C Autoclave test with rotating sample holder providing a velocity of 10 ft/sec. Samples were exposed to fresh sea water, replaced every 15 days, at 350 F. Ref: U. S. Naval Experiment Station, "Testing of Various Materials in High Temperature Waters", EES Report 040028D, 30 November 1953.

Test D Autoclave test, 0.5 ft/sec, 54 days in 325 F sea water. Ref: Stewart and LaQue, Corrosion, Vol 8, No. 8, p 259-277 (August 1952)

(a) These samples were on test for 45 days.

(b) G = slight gain in weight due to stains at contact with fixture.

The metal with the most outstanding promise for heat exchangers involving sea water is titanium. Titanium, unlike other metals, normally does not pit, is not susceptible to stress corrosion, is free from local corrosion under fouling organisms, is free from impingement and cavitation attack at velocities which attack copper-base alloys, and is not susceptible to sulfide attack in contaminated sea water. Titanium and its alloys can be provided in the forms of sheet, tubing, or forgings. Some progress has been made in finding a method of producing coatings. Titanium and its alloys are less susceptible to scaling in sea water than other metals. Even though the thermal conductivity is low, the over-all efficiency is considered to be much greater in typical sea-water applications. The chief disadvantage of titanium is price, but some of this expense can be absorbed in the over-all cost of the equipment.

In choosing materials for sea-water heat exchanger or evaporator service, one must also consider the forms available. Only materials available in wrought forms, such as tubing and sheet, have been discussed in this review. In all cases, the materials can be fabricated by usual methods including welding. While the thermal conductivity varies greatly, the property of interest to the designer is the over-all rate of heat transfer of the metal in its service environment. Experience has shown that, while the relative costs of materials of construction may vary as much as 20 to 1, the finished installation at the site may only vary say 3 to 1. If titanium were used, for example, savings resulting from lower freight charges, reduced maintenance, on service life, and greater over-all efficiency would at least partly compensate for the much higher initial cost of the metal.

Recommended Materials of Construction

At the present time, it is recommended that the heat-transfer surfaces of the evaporator and the heat exchangers be made of the 70-per cent copper, 30-per cent nickel alloy with 0.7 per cent iron. This alloy has given excellent service in heat exchangers aboard ship under a wide variety of service conditions.

Considerable research would be needed to demonstrate the possibility that useful life could be obtained by an all-aluminum design. Such a design probably could be evolved, but one would anticipate higher maintenance and replacement costs than for cupro-nickel alloy construction.

Titanium appears to warrant careful consideration as a material for the heat-transfer surface in evaporators of sea-water stills.

FUTURE WORK

Inasmuch as this project will terminate on March 15, 1957, only a few additional tests are planned. These will be directed toward confirmation of previously obtained comparative data on film and dropwise condensation.

Concurrently, a summary report on the research on the evaporator will be prepared. This report will include the data obtained during the experimental phase of the project, and will present a suggested design of an improved evaporator for thermocompression sea-water stills.

(Data upon which this report is based may be found in Battelle Laboratory Record Book No. 11959.)

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