COUNTERFLOW HEAT INTERCHANGERS

THESIS FOR THE DEGREE OF M. S.
Roy D. Nestle
1933

Heat

Physics

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Acknowledgment

To Doctor Clark Wells Chamberlain who suggested the problem of counterflow heat interchangers, gave valuable guidance in its solution, and aided in the overcoming of the obstacles in the experimental work.

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Object of the Problem

The purpose of this thesis is to discuss heat transfer in counterflow heat interchangers by systems employed up to this time and to present another method described for the first time in this thesis.

A counterflow heat interchanger is the system by which heat is passed from the medium of higher temperature to a medium of lower temperature as the two media pass by each other traveling in the opposite direction. The quantity of heat transferred is a direct function of the difference in temperature between the two materials. For the materials which it is convenient to use perhaps one or both may be poor conductors of heat, which greatly adds to the difficulty.

In the condensers, cooling towers, or other forms of heat interchangers used up to the present time, the temperature difference of the media was at least 20 degrees Fahrenheit and usually greater. The degree of success of the mechanism for which the counterflow heat interchanger is being constructed, depends on this temperature difference; and a practical efficiency is only possible with a low temperature gradient.

By subdividing the counterflow materials and having them in direct contact, the rate of transfer of heat has been enormously increased. This thesis describes the method, which is practical, even though it reduces the temperature gradient to a minimum value hitherto unachieved.

Introduction

The problem undertaken is the method of transferring heat from vitiated air in an inclosed space to fresh air admitted to that space. The problem is solved by using two columns. In one, the vitiated air moves up yielding heat to water passing down. In the second column, the heated water moves down giving up its heat to fresh air coming up.

When heat passes from one body to another, it does so by one or more of three methods: conduction, convection, and radiation.

The molecules in any material are constantly traveling in an undirected motion. The kinetic energy of this vibratory motion is the heat possessed by the body; and what we call temperature is the heat intensity of an average value of these motions. The elastic impacts may cause a condition such that, for an instant, one particle is perfectly still and another has twice or three times the average velocity; but when the particles are close together, the collisions are frequent and the kinetic energy of any one particle is changing frequently. If heat is applied to one layer of molecules, their increased velocity will soon be shared by impact with colder particles, in turn, share with their neighbors. The passing of energy along by collision is called conduction. These motions are very rapid, but the collisions may be head on or any kind of a glancing blow so the energy is quickly diffused in all directions and between several molecules. In metals, the energy of one particle in going one millionth of an inch would probably be shared with a half dozen other particles so the transfer of heat by conduction is necessarily slow. The electrons, being very much smaller than the molecules and atoms and being able to move in the interstices between the molecules, are probably the most effective agents in transferring energy from one molecule to another. This belief is further substantiated by the fact that good conductors of heat are also good conductors of electricity.

It has been found by experiment that the rate of flow of heat through a material is proportional to the difference of temperature $t_1 - t_2$ of the two faces; inversely proportional to the thickness d of the slab; and proportional to the area of the faces. Then the rate of flow of heat in calories per second $= \frac{k(t_1-t_2)}{d}$ area. For any one material, k is a constant which is called the coefficient of thermal conductivity. For silver, or copper, k is relatively large; but for materials such as wood, water, and air, it is very small. The two fluids then, that is, water and air which would be desirable to use, are very poor conductors of heat.

An attempt was first made to pass the heat from one column to the other through a thin copper wall which is a good conductor. However, the molecules of copper attract by gravitational forces a layer of air one radius of molecular attraction in depth. Dr. C. W. Chamberlain measured this distance (Phy. Rev., 31, 170, 1910) and found it to be $6(10)^{-7}$ centimeters. We then have a stationary non-conducting layer on each face of the copper, and an enormous surface would be required to pass the quantity of heat necessary with a reasonable temperature gradient. D. A. Low, when examining the heat entering a steam boiler, found 2% of the temperature head was required to penetrate the water layer on the inside of the boiler, 1% for the boiler plate, and 97% for the air layer on the plate. This observation proves very definitely from practical experience, the enormous resistance to heat flow caused by this barrier film of air. A counterflow system like this would be desirable, then, only when the counterflow materials could not be mixed.

In conduction, heat is transferred through bodies the parts of which, except for possible molecular and electronic diffusion, are at rest relative to each other and to their bounding surfaces. Where such relative motion does occur and is associated with temperature gradients, heat is conveyed by the moving matter and is then said to be transferred by convection. The phenomenon is practically limited to fluids and under ordinary conditions, it occurs readily in them.

It is usual to distinguish two types of convection currents, namely, natural and forced. The former are essentially gravity currents which are caused by differences in density in the body of a fluid due to differences in temperature. The latter are due to extraneous causes, and they may modify or completely obscure the natural currents. The subject of convection is still in a comparatively undeveloped stage, nor is this to be wondered at when it is realized that the problem of calculating the heat conveyed by a moving fluid involves a combination of the Fourier equations of conduction with those of hydrodynamics. The simplifying assumptions necessary to obtain solutions have, as a general rule, restricted seriously the usefulness of the results. In one of our columns, water is being heated while falling through the conduit making the natural convection current oppose the forced convection flow. In another of the tests made, this was a serious difficulty and will be pointed out later when this test is considered.

A modification of this type of heat transfer is found in the case when air is bubbled through a water column. As the air rises through this column, it will be saturated with water vapor. In this condition of equilibrium, the molecules with the greatest kinetic energy will be going from the liquid while an equal number will be going back to the liquid. Or before equilibrium is reached, there will be saturation near the surface of the bubble with the number of water molecules per unit volume decreasing toward the center. In either case the boundary is an active one with the liquid molecules leaving and returning. When once the water molecules are out in the air, the impacts soon bring them to the same temperature as the air. Instead of passing heat along by conduction, it is being bodily carried from one place to another and essentially convection, although there is no mass movement.

The term radiation is the name given the process of transferring energy from a body across space and it is now generally accepted that this form of propagation of energy, which we call heat radiation, is a wave motion. All heat problems where heat is to be confined at a temperature above the surrounding temperature, are made more difficult because of radiation.

Present Heat Transfer Systems

Hot Water Heater

One of the first water-air heat interchangers was the hot water reheater of the Mekarski system as used on a number of compressed-air railways in England, France, and Switzerland. The heater is first charged at the station with water at about 100 pounds or more pressure at a temperature of about 338° F. or greater, containing nearly 1,200 heat units per pound of water. In the early water rehaaters of this class, the air was injected from a nozzle in the bottom of the heater and allowed to rise through the water thereby absorbing water vapor to saturation and with but little excess of steam. In the heater of this type used on the Nantes, France, compressed-air tramway, the compressed air enters the heater at the side near the bottom, and is divided into small streams issuing from a perforated pipe, and, bubbling up through the water, becomes heated nearly to the temperature of the water, and also takes a considerable excess of hot vapor or steam, depending upon the relative pressures of the air and the pressure due to the temperature of the water.

The Mekarski system uses a diaphram above the water line which serves to prevent particles of water from escaping through the reducing valve when thrown up by the agitation of the passing air. Above this diaphram is an especially constructed valve which opens and closes automatically and regulates the pressure that will prevail in the cylinder of the compressed-air engine.

The purpose of the heating in this system is to increase the volume of air before it reaches the cylinder. The temperature gradient is not uniform throughout the heat exchange, but is greatest at the bottom and gradually diminishes as the air is heated. Also the turbulence set up in the tank does not ruin the system. In an efficient counterflow heat interchanger, the turbulence and large temperature gradient could not be allowed.

Air Cooling by Ice

The apparatus commonly employed for cooliig air usually consists of racks or trays containing ice and the air is passed through these cakes of ice on the way to the various rooms of the building. The arrangement of the ice blocks is important; that is, the air must be brought into close contact with them if the melting is to be rapid and the cooling effective. Here only the air is moving,but this produces a relative motion of the ice and air. A large temperature gradient is tolerable because only partial cooling is desired.

Air Cooling by Water Pipes

Another method of cooling air is to have cold brine or other refrigerating liquids flowing in pipe coils and passing air over them. It has been attempted in many cases to perform the work with coils filled with water at ordinary temperature, but the results were not entirely satisfactory. The circulation of city water, or, in the case of manufacturing establishments of private artesian well water through the coils of the air cooler during the summer reduces the temperature of the fresh air discharged in the building from 3° to 10° F., depending on the temperature of the water.

Open Surface Coolers

Similar to the cooling by water pipes is the open surface coolers. In this form of apparatus, hot liquids are cooled by allowing them to flow down, exposed to the atmosphere, over metallic surfaces, on the other side of which passes cold water. Its cooling surfaces consist of straight or bent tubes arranged one above the other; the section of a tube is circular, oval, or approximately triangular. More rarely, plane surfaces, verticla, or inclined, or vertical tubes are used.

The following table gives a set of readings taken on an apparatus of this type: where

t_{wa} = original temperature of the cooling water

t_{we} = temperature of the cooled water

O_m = mean temperature difference

H_k = sq. meters of copper cooling surface

W = liters of cooling water to cool 100 kilos. of liquid and the original temperature of the liquid to be cooled = 100° C.; temperature of the outflow of cooling water = 90° C.

t_{wa} (C)	2°	5°	5°	5°	10°	10°	10°	15°	15°	15°
t_{we} (C)	3	6	10	20	11	15	25	16	20	30
O_m (C)	3.9	3.9	7.2	12.4	3.9	7.2	12.4	3.9	7.2	12.4
H_k	2.5	2.4	1.2	.65	2.3	1.2	.60	2.2	1.1	.56
W	111	111	107	94.2	112	107	94	112	106	94

The cooling water enters below and leaves above while the water to be cooled flows down so it is a counter current. The cooling action of this apparatus is generally very good, and, as shown in the table, a mean temperature gradient of as low as 3.91° C. was obtained. These results are better than the results from systems previously described because the thin layer of liquid greatly favors the transfer of heat, and because the velocity of both liquids - the cooling and the cooled - may be greater here than in closed coolers, since the air itself takes up heat and by evaporation accelerates the cooling, and, finally, because the surfaces are easily accessible and can, therefore, always be kept clean and active. A small amount of the heat is also lost by radiation.

It will be noticed that the heat loss due to cooling by evaporation is not confined in the cooling liquid, but goes out into the atmosphere and is lost. The design of the heat interchanger worked out in this problem must be such that the heat is confined to the media of exchange, because the first cycle is linked to a second where this heat must be given up.

Cooling by Water

Instead of passing the water through pipes, a common practice is to raise the water several feet and to distribute it over a simple cooler constructed of thin boards over which the water is allowed to trickle in cascades, and placed in an exposed position so as to be acted upon by the wind. Or, when the cooled air is used in buildings, the boards are arranged in shelves, slightly inclined, and built in an inclosed structure through which the air can be pumped.

Cooling Ponds

In commercial work where cooling water is needed, it often happens that a continuously fresh supply of circulating water is not available, and then the hot water must be recooled to be used over. Often a cooling pond is used. Often a cooling pond is used. The hot water is usually conducted by a shallow open channel a few feet wide to the farthest point in the pond, and the cold water is taken at a point nearest the place to be used. The volume of water in the pond also forms a reserve to draw upon should the make-up supply be temporarily stopped. The major portion of the cooling is due to the evaporation of some of the water, but some heat is transmitted to the air above the pond.

Cooling Towers

When there is not sufficient reservoir capacity or exposed area, either cooling towers or sprayers are in common use. In the cooling tower, the water is raised to a height of 25 feet or so, and is then allowed to trickle or splash over the surfaces of a series of rods, boards, drain tiles, or galvanized wire mats, as it descends to the tank below the tower.

With chimney coolers, the cooling portion of the tower is enclosed except for the openings for the air at the bottom. Above this cooling portion, the tower is formed into a chimney to induce a draught or current of air through the tower, giving a total height of 60 or 70 feet above the tank. Fan coolers of the same type are more certain and more effective in action than chimney coolers. With these, the air is usually forced into the tower by motor driven fans placed at the base; and although this type of cooler requires less ground space than the chimney cooler, the cost of upkeep militates against the general adoption of the fan cooler.

The data on one tower given by Hausbrand illustrates the important facts. The cooling tower, with many steps and a natural access of air, 3 x 12 = 36 sq. m. in ground area, 480.0 cm. high, and with 322.5 sq. m. of wooden surface over which the water flowed, cooled 22,800 liters of water in one hour from 50° to 20° C., when the air entered at 2.5° C. and left at the different stages at 8.5°, 14.5°, and 20.5° C. The calories given up in cooling by the water, C_k, were

$C_k = 22800\ (50-20) = 684{,}000$ calories

1 kilogram of saturated air at 2.5° C. contains .0046 kilo. of water.

1 kilogram of saturated air at 8.5° C. contains .0069 kilo. of water.

1 kilogram of saturated air at 14.5° C. contains .0107 kilo. of water.

1 kilogram of saturated air at 20.5° C. contains .0153 kilo. of water.

The mean of the last three numbers is .01096 kilo.

If the air which leaves the staging is only saturated to the extent of 80 per cent, then 1 kilo. contains $.01096 \times .8 = .008768$ kilo. of water. 1 kilo. of air thus has taken up by evaporation $.018768 - .0046 = .00416$ kilo. of vapor, which corresponds to 2.496 calories.

The air is heated on the average from 2.5° to 12.5°, i.e., through 10° C., consequently 1 kilo. has taken up by being heated 10 x .2375 = 2.375 calories.

Thus 1 kilo. of air takes up a total of 2.496 - 2.375 = 4.871 calories.

Of the total quantity of heat to be abstracted from the water, the air takes

by evaporation, $\frac{2.496 \times 684{,}000}{4.871} = 350{,}494$ calories

by heating, $\frac{2.375 \times 684{,}000}{4.871} = 333{,}506$ calories

The surface of the apparatus over which water flowed was	322.5 sq. m.
The wetted surface underneath, estimated	60.0
The surface of the falling drops was about 6 sq. m. per 1000 liters, or 6 x 22.8 =	136.0
Total surface	518.5 sq. m.

It is noted from the data that the average temperature gradient is about 23° C. and that 1320 calories of heat is transferred across 1 sq. m. of surface in the one hour; also that a little over 50% of the cooling was due to evaporation.

Spray Cooling

In this system, spraying nozzles are fixed upon a system of pipes over the cooling pond. They are commonly placed at an elevation of several feet and the spray is allowed to fall into the pond, the object being to expose the maximum surface of water to the atmosphere so as to facilitate rapid evaporation and cooling. The water has to be supplied to the spraying pipes at a pressure of 18 feet or more of water to get effective spraying.

Surface Condensers

The appliances by means of which vapors or gases are liquefied are known as condensers, and are divided into two classes: Jet condensers, and surface condensers.

Surface condensers are essentially the air cooling devices already described, with vapor substituted for air. The exchange of heat takes place through a metal wall and, therefore, they are more expensive to operate than the jet condenser. This type, therefore, is never used, unless it is required to separate the vapors of valuable liquids or to obtain pure condensed water.

Jet Condensers

In the jet condenser, the cooling water is injected directly into the vapor to be condensed. In the wet condensers, the air pump extracts the condensed vapors and the injected water, together with the air and uncondensed vapors. Wet condensers are generally arranged for parallel currents. Then there is the so-called dry condensers from which the air pump extracts only the air and uncondensed vapor, while the condensed vapor and injected water are carried off automatically in another way.

In the wet jet condensers, the steam enters the closed condenser at the top, together with the water which is in a fine spray, and both move downwards with diverse velocities. The steam then gives up its heat to the cooling water and is liquefied, and the cooling water takes up this heat and becomes warmer. The velocity of the steam diminishes to zero in its downward path, the velocity of the water increasing downwards in accordance with the laws of falling bodies. Air, water, and uncondensed gases collect at the lower part of the condenser and are exhausted by the air pump.

The "dry" jet condensers, which are almost always constructed to work with counter currents, are closed vessels, with the steam to be condensed entering at the bottom, and the well-sprayed cooling water at the top. The heated water flows away spontaneously, together with the condensed steam, by means of a fall pipe or barometer tube at the bottom, while the air and gases are exhausted cold at the top. Dry condensers are often used for small and medium capacities, and for large capacities almost invariably. For a condenser, in which the water falls straight to the bottom without steps, the height must be very great, and the water very finely divided, if the water is to be heated nearly to the temperature of the steam. A very fine spray of water is not easily obtained and necessitates a slowly rising current of steam. Therefore, dry condensers without steps must be very high and have a large diameter.

The heat transfer will be much more complete if the water is allowed to fall through the same total height in several short stages, by each of which it is given a fresh surface. Since the velocity of fall is the least at the beginning, the period during which the water is in the condenser increases with the number of steps, as also does the number of changes of surface. It is naturally endeavored to make the temperature of the waste water approximate as nearly as possible to that of the steam. Experience shows that with 5 or 6 steps, and a total height of 250 to 300 centimeters, very warm waste water may be obtained, even when the water is injected in jets of 6 or 8 millimeters in diameter. A finer spray of water and more steps improve the action.

Method of Solution

From the discussion of heat transfer, it would be agreed that the most effective means of transferring heat was by convection or the bodily carrying of heat from one place to another. Also, in the description of heat transfer devices, it was generally concluded that the most efficient to operate were the ones where there was an active boundary between the cooling and cooled phases. Since the two phases must again be separated, this active boundary can best be obtained by using a liquid and a gas.

Cooling Water by Air

When water is cooled by air, the cold air has a twofold cooling action on the warm water. In the first place, it acts directly by abstracting heat and itself becoming hotter. If the atmospheric air, at its first contact with the water, has a temperature t_1, and leaves it at t_2, then L grams of air take from the water in being heated.

$Q_1 = .2375\ L\ (t_2 - t_1)$ gm. calories where Q_1 is the gm. calories due to heating.

And in the second place, the air cools the water by causing a portion of it to evaporate. The atmospheric air, which is practically never saturated with moisture, readily takes up more, especially when it is warmed, as by the water in this case. If one gram of air before contact with the water contains d_a grams of vapor, and on leaving the water d_e grams, this 1 gram of air has taken up during contact $(d_e - d_a)$ gm. of water vapor. If the mean temperature of the water was t_m, then the approximate number of gram-calories, Q_2, withdrawn from the water for the evaporation of the water taken up by L grams of air was:

$$Q_2 = L\ (d_e - d_a)\ (610 - t_m)$$

The total amount of heat, Q, which the air takes from the water is:

$$Q = Q_1 \quad Q_2$$

$$Q = L \quad .2375\ (t_2 - t_1) \quad (d_e - d_a)\ (610 - t_m)$$

If W grams of water at the temperature t_3 are to be cooled to the temperature t_4, then the heat required for this purpose, Q_3, will be:

$$Q_3 = W\ (t_3 - t_4) \text{ gm. calories.}$$

The heat gained by the air equals the heat lost by the water, so $Q_3 = Q$ or $W(t_3 - t_4) = L \quad .2375\ (t_2 - t_1) \quad (d_e - d_a)\ (610 - t_m)$

The temperature, t_1, of the external air varies considerably, and so does the quantity of moisture in it. Even though t_1 was constant, the quantity of water would vary with the humidity so the conditions of the cooling air will not be constant.

If sufficient operating data are known, the surface, S, to produce the desired cooling, can be calculated. Again, if Q_1 is the heat to be taken from the water to warm the air, not for evaporation; Z the time of cooling in hours, t_m the mean difference in temperature between water and air, k_e the coefficient of transmission, then

$$Q = Z\ S\ k_e\ t_m$$

and the surface requisite for the cooling by means of air is

$$S = \frac{Q}{Z\ k_e\ t_m}$$

Or more often the coefficient of transmission is not known so by measuring Z, S, t_m, and Q, we can compute k_e from

$$k_e = \frac{Q}{Z\ S\ t_m}$$

This value is the common measure of heat transmission and k_e may be defined as the quantity of heat which will pass through unit surface area in one hour with a one degree temperature gradient.

From experimental work, mathematical formulae have been derived in a few cases for this transmission coefficient. Where V is the velocity of the air in meters per second, the coefficients are:

(1) for cooling tower in which drops are abundantly formed

$$k_e = 2 \quad 18 \quad V$$

(2) for plane surfaces over which the water flows

$$k_e = 2 \quad 12 \quad V$$

(3) for water at rest

$$k_e = 2 \quad 10 \quad V$$

The surface which the water presents to the air must change as frequently and rapidly as possible, for heat penetrates slowly into a mass of water at rest. The external layer is rapidly warmed, but heat enters the interior very slowly because this action is governed by the laws of conduction. The best water cooling apparatus will thus always be in the form where the water is finely divided and the surface changing often.

Cooling Air by Water

Atmospheric air always contains more or less moisture in the form of vapor. The maximum amount of vapor in one cubic centimeter of air is equal to the weight of 1 c.c. of saturated vapor at the temperature of the air. If air which contains much moisture is considerably cooled, it generally reaches a condition in which it can contain only a smaller weight of vapor, and, consequently, the excess of vapor must separate or condense. Thus, if a certain volume of air is to be artificially cooled in a certain time, it is necessary to take from it the heat required, first, to cool the dry air itself; and, second, to condense the vapor which must be separated.

If L equals grams of air cooled, t_1 equals the temperature before cooling, t_2 = the temperature after cooling, d_a = the weight of vapor in 1 gm. of air before cooling, d_e = the weight of vapor in 1 gm. of air after cooling, and t_m = the mean temperature of the air, then in order to cool the air from t_1 to t_2, it is necessary to abstract the following amount of heat:

$$Q = L \quad .2375 \ (t_1 - t_2) \quad (d_a - d_e) \ (610 - t_m)$$

The necessary quantity of cooling water depends on its initial and final temperature and is

$$W = \frac{Q}{t_4 - t_3}$$

The same laws for cooling surface and coefficient of transmission are as applicable here as they are in the discussion of cooling water by air.

Air: The Continuous Phase and Water Dispersed

The mean specific heat of air between 0 and 100° C. is .2374 calories per gram. Or this means that 1 gm. of water has the same heat capacity as 4.212 gms. of air. One gram of water is 1 cubic centimeter and 1 gram of air equals 769.2 c.c. Therefore, 769.2 x 4.212 = 3250 c.c. of air is equivalent in heat capacity to 1 c.c. of water, and the rates of the volumes are:

Water: air :: 1: 3250. This value does not take into account the heat used for evaporation, or that given up in condensing; but even then, the ratio of water to air would ordinarily not be greater than 1:1600.

With such a relatively small part of water, the easiest method would seem to be to spray the water in a rising column of air and have the heat exchanged while the water is falling. The water must be finely divided if it is to give up its heat. Water may be dispersed into small droplets with a spray nozzle and high pressure water, or by the venturi jet. In either case, this will be extra work added to the work of pumping the water back through the distance it falls by gravity through the conduit. If the droplets were not all of the same size, the largest could not be larger than would give up their heat in falling the length of the column.

When the water globules are very small, there is a large frictional resistance per unit volume, and the velocity of fall by Stokes' law is

$$V = \frac{2\, g\, a^2\, \sigma}{9\, N}$$

Where a is the radius of the drop, σ is the density of the drop and N the coefficient of viscosity of the gas through which the drop is falling. For small drops, this velocity is smaller than the velocity of the rising air and the droplets are carried up instead of falling. The droplets might be given sufficient velocity at the start so that their kinetic energy would carry them to the bottom, but this would require work that could ill afford to be spent.

Another difficulty is the distribution of the globules in the column. The air moves fastest in the center of the pipe and falls off to zero at the edge. There will be less resistance where the air velocity is least, so the water drops will be shunted to the side instead of falling through the center where they are most needed.

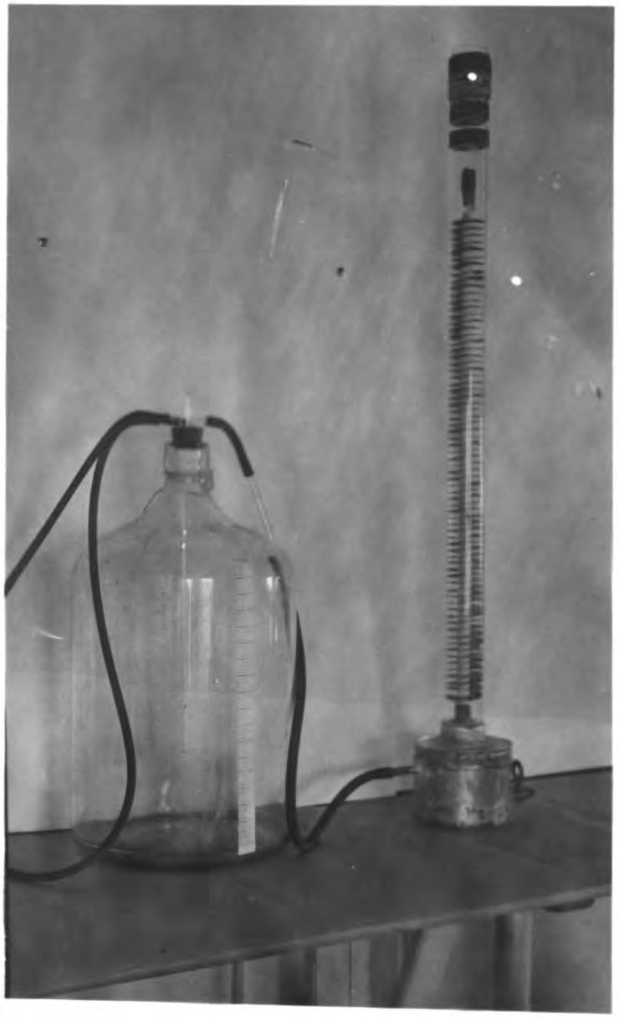
The method of dispersing the water in the air is desirable because it would involve the least amount of work if the water could be divided without too much work. To eliminate the spray difficulties, an attempt was made to get the water in very fine sheets. By having the water in sheets, it would be uniformly distributed and it also could be directed.

To form this apparatus, very thin copper sheets, approximately .001 inch thick, were built up in a tier. Each sheet had a circular hole in the center, so that when the tier was built up there was a cylindrical opening in the middle of the block. The sheets were then clamped together and water under pressure applied to the center cavity. With the sheets clamped very tightly together, a surprisingly large amount of water passed through the narrow openings, but it coalesced at the outer surface and did not continue as sheets.

Brown and Larmor, when examining the rate of diffusion of a gas through small narrow openings, found that the amount of gas diffused in a definite time was proportional to the perimeter of the opening and not to the area as would be expected. Also, in 1874, Stefan was investigating experimentally the rate of evaporation of a liquid in a tube whose open end is in free communication with the outer air, and he demonstrated that the theory of the diffusion of gases is strictly applicable to a case of this kind. It is interesting to know that in nature we find an application of this fact. The stomata in leaves are narrow slits of an elliptical shape and a great quantity of evaporation takes place from them. The elliptical opening gives more perimeter than a circle of the same area and, therefore, gives more effective evaporation for the limited area exposed.

The reason for this perimeter law and the large quantity of water passing through the narrow openings between the sheets of copper, may be explained by the viscosity action in these narrow capillaries. The coefficient of viscosity of a substance is measured by the tangential force on unit area of either of two horizontal planes at unit distance apart, one of which is fixed, while the other moves with unit velocity, the space between being filled with the viscous substance.

Imagine two adjacent layers of fluid, one moving with a velocity V, the other with a velocity $V + \Delta V$. If now a particle from the slower moving layer moves through the intermediate surface, and a particle of equal mass moves across the intermediate surface from the rapid moving layer to the slower, the effect will be, on the average, to decrease the momentum of the $V + \Delta V$ layer and to increase that of the V layer. This is the same as saying that at the bounding surface - a purely mathematical surface drawn in the fluid - there is a force which slows up the $V + \Delta V$ layer and accelerates the slower layer. But this tangen-



Spiral Liquid Column

PLATE I

tial force is the force of viscosity from which we get the ordinary coefficient of viscosity defined above. Now if the distance between the copper sheets is 3R, where R is the radius of molecular attraction, then on each side there will be a 1R layer of water which is tightly vound and a 1R layer in the center not bound by the copper. This center layer can sheer over the two outside layers without the viscosity effect because the molecules in these layers are bound and do not jump out into the moving fluid. The frictional resistance is greatly decreased as a result, so the flow will increase correspondingly. Because of this, the flow will also vary with the perimeter in tubes of capillary size.

Water: The Continuous Phase and Air Dispersed

Another possibility of a gas-liquid counterflow is to bubble the air through a column of water. For this test, a glas tube 5 cm. in diameter was used for the conduit and a fine glass nozzle was used to blow the bubbles. It was found that when the bubbles are small, there is little tendency for them to coalesce while they are in the water.

The work required to blow a bubble under a head, h, of liquid would be the same as taking the same quantity of air and lowering it in the liquid until there is the same head, h. The volume of the bubble will change with the head because of the changing pressure, so let V be the average volume of air in the bubble, and, if σ is the density of the liquid, a weight of liquid, m, equal to σV is displaced and the buoyant force = $F = mg = \sigma Vg$. And the work, W_1= force x distance or here $W_1 = \sigma Vgh$, and o is unity for water.

To compare this work with the work in spraying water, take a volume V of water the same as the volume of air above and the work, W_2, required to raise this a distance h is $W_2 = \sigma Vgh$. Therefore, $W_1 = W_2$, or the work required to blow a volume of air, V, through the liquid is the same as the work required to lift this same volume of liquid a distance equal to the head at which the air is bubbled out. From the previous calculations of the heat capacities, we found that the volume of air used was about 3000 times the volume of the water, so the work in this method is increased about 3000 fold over spraying the water.

Because of the buoyant force, the bubbles rise very rapidly, giving very little time for heat transfer. Also, the bubbles cause considerable turbulence, which will mix the warm and cold water which should be gradually changing from hot to cold in going from one end of the tube to the other. This mixing motion will be aided by natural convection currents in the column where hot air enters at the bottom. In this column, the condition would be that the coldest liquid is at the top and the warmest at the bottom, and the water moves down so slowly by forced convection that the natural convection current opposing it is very serious.

To decrease this large head and hence the work in blowing the bubbles, the water column was made nearly horizontal. In this position, there was draining of the bubbles because there was not sufficient head for the water to run back.

The next attempt was to spiral the air bubbles through a helical path. The spiral shown in Plate No. 1 was made by linking paper circles. The centers of the circles were punched out and the helix was drawn out into the spiral, using a glass tube $1\frac{1}{2}$ cm. in diameter for the core. The paper part was coated with paraffin to make it water proof, and the whole spiral was placed in a tube approximately 5 cm. in diameter.

For the same length of path, this method increased the time the bubbles were in contact with the water because the component of the buoyant force tending to push them along the helical path is much less than when they are allowed to rise vertically. The magnitude of this force along the path is directly proportional to its pitch. Another desirability of the spiral is because, for the same length of path, the head of water is much smaller and less work is required to blow the bubbles. When the column is filled with air bubbles and the air bubbles are close together, approximately half of the space is air and half water.

Thus we would have a column possibly 2 feet in height with only a 1 foot effective head. Again the difficulty was buoyant force, because even though the bubbles couldn't rise directly to the top, they rose to the top of the spiral path, marked "a" in Plate No. 1, leaving the water below in layer "b". The bubbles at the top drained out so the effective surface is practically confined to the surface between the layers a and b, and this did not give the desired cooling surface.

The Transfer of Heat in Foam

Condition of Water and Air in Foam

When an air bubble rises to the surface of a liquid, a second liquid-air film is formed concentric with the film present, while the bubble is immersed. These two films form a shell of liquid which incloses the air. If the films are stable, another bubble rising up under the first pushes it out while the third pushes out the second, and so on, giving a column of foam. The foam walls are plastic, and tend to fill all space so the foam bubbles no longer remain spherical, but become hexagonal in shape. The forming of film requires work and the hexagon is the figure which has the smallest surface, and yet takes up all space, so, for this reason, the hexagonal figures are the most stable form.

Now if some of the same liquid from which the bubbles are blown is poured on the top of this rising column of foam, we will have a condition similar to the water passing through the copper sheets. The walls of the foam are already formed, so the excess solution passes between them as it did between the two water films, one radius of molecular attraction thick, which were bound to the copper. There is then very little viscosity, so the liquid falls by gravity quite rapidly, even though it is in very fine sheets.

A foam bubble about .6 cm. in diameter was found suitable for the heat interchanger. Smaller bubbles would give more cooling surface in the same volume, but they are more difficult to break and more work is required to make them. The volume of air inclosed in a bubble of .6 cm. diameter equals $4/3 \pi r^3$ where $r = .3$ cm., or this is .113 c.c. The films are approximately 1 or 2 u in thickness, and the volume of liquid in each bubble is $4\pi r^2 t$ where t is the thickness or this is .00024 c.c. The heat capacity of the liquid, then, in a bubble of this size is about 7 times that of the air it carries. But this is not a serious difficulty, because when the bubble breaks at the top, this liquid runs back down, giving up or taking in heat, as the case may be, to the rising bubbles. When the velocity of the air is constant, the heat capacity of the bubbles going up and of the liquid from the broken films coming down are equal, and the two effects cancel out. This extra heat will have to be transferred, but it is transferred between the liquid in the film wall and that in the interior of the film, and this transfer is very rapid.

In a system of this type, we not only have the desirable qualities of an active liquid-air surface and finely divided liquid, but we also have a large cooling surface in a small volume. In the foam bubble of .6 cm. diameter used above, there is 1.13 sq. cm. area for a volume of .113

c.c. Or, in a 1 liter volume, there would be 10,000 sq. cm. of cooling surface, which is nearly 11 sq. ft. This large cooling surface in a small space helps to make the heat interchanger more compact and is probably as important as a suitable heat transfer boundary.

When the liquid is being cooled, the warm solution between the films is very thin; and by bombarding, the molecules in the film surface soon come to the same temperature as the film. But the films themselves are only a few molecules thick, so the heat is quickly transferred to the air layer where this active boundary gives up the heat to the water. By heating the air, its capacity for holding moisture is increased, and so the cooling of the liquid is aided by a portion of it going out as vapor. In cooling the air in the other column, this moisture must be condensed so the heat due to cooling the air and also that necessary to condense the vapor must pass back into the liquid and the condensing here works against the transfer of heat by increasing the quantity to be transferred. The effect will be to make the heat transfer coefficient seem smaller even though the boundary is just as active. Because of this, more cooling surface will be required for the air cooling chamber.

Stabilizing and Breaking the Films

Freunlich, in 1909, found that no pure liquid can give a stable foam. Later, Bancroft found that, to get a foam, the only essential is that there shall be a distinct surface film - in other words, that the concentration of the surface layer shall differ perceptibly from that in the mass of the liquid. All solutions will, therefore, foam if there is a marked change of surface tension with concentration, regardless of whether the surface tension increases or decreases. All colloidal solutions will foam if the colloid concentrates in the interface or of it is driven away from the interface. To get a fairly permanent foam, the surface film must either be sufficiently viscous in itself, or must be stabilized in some way. This can be done by introducing a solid powder into the interface, The vapor tension of the liquid must also be low or evaporation will weaken the film to a point where it will rupture.

Miss Pockels and Lord Rayleigh investigated the manner in which surface tension of a contaminated water surface varies with the amount of contamination; and their results give a good explanation of the stability of films. They measured the surface tension of a water surface as oil was sprinkled onto the water. The surface tension of pure water is 73 dynes per cm., and as oil was added, the surface tension remained about 73 dynes per cm. until a layer of oil 1 uu was added, and then the surface tension suddenly dropped until, by the time a 2 μμ layer was added, the surface tension was practically that of oil. It is a well-known fact that a thin layer of oil will calm the waves on rough water. When a layer of oil is on the water, the wind will tend to pile the oil up in one place and thin it in another; but when it does this, the surface tension of the thinned part is nearly that of water, while that on the crest of the ripple is the surface tension of the oil which is 30 dynes per cm., and the greater surface tension of water pulls the crest down and prevents a wave from starting.

The same explanation can be used to explain the stability of foam. Soap, saponin, or even dirt, lowers the surface tension of water; and it is an observed fact that the soap is more concentrated in the surface layer, so when the film thins, a greater surface tension is immediately set up in the thinned place and this force pulls in the stabilizing agent to strengthen the spot. It is the maintaining of this equilibrium which gives a stable film.

W. C. Preston measured the stability of soap films by what he called "foam power". He took 100 c.c. of the solution of a definite concentration, and after agitating it for 2 minutes, he allowed it to set one minute, and then measured the percent of the 100 c.c. of solution that was still in foam. The value would vary with the amount of agitation, temperature, size of bubbles, and so forth, so it would be only a rough measure at best. In this way he found that aging the soap solution exposed to the air greatly reduced the foam power. This he attributed to the absorption of carbon dioxide from the air. The foam solution in the interchanger will be used over and over so a solution must be used which will hold its foaming properties for at least several days.

The solution used in the interchangershould make films stable enough so that they will not coalesce before they reach the top of the column and not so tuff that it will be difficult to break them. Also the solution must make a stable foam at about 90° F., and yet not freeze at -10° F. Calcium chloride, sodium chloride, and potassium chloride all coagulate the soap and destroy the foaming power. Di ethylene glycol was tried because of its low freezing point, but a suitable stabilizing agent could not be found for it. The best solution found was a water, glycerine, and castile soap mixture. Just enough glycerine was used to lower the freezing point below the temperature at which it was to be used.

The foam can be broken by a chemical substance which counteracts the stabilizing agent, but this permanently destroys the foaming power, so a mechanical means must be used which does not contaminate the solution with undesirable substances. An object which is wet by the solution is an ineffective breaking agent, because the film clings to the object and keeps the bubble sealed. It is, therefore, necessary to use a sharp object which will pierce the film and which will not be wet by the solution. Bronze wool pressed into a compact plug was the most satisfactory method employed.

Mobility of the Liquid

If a large bubble is blown and a drop of the solution is placed anywhere on the film, even the bottom, this drop quickly spreads itself over the entire surface unless the film is already at its maximum thickness. The reflected light from the surface of the bubble makes the currents plainly visible, and this action is very rapid. The unbalanced forces in the film make it very dense, and, hence, the solution is under a great pressure. Mobility increases with pressure, so this accounts for part of the rapid motions.

The liquid film itself is not changing molecules rapidly with the liquid inside the two film surfaces. If a column of transparent bubbles are blown and then a colored solution is allowed to run through them, the bubbles remain transparent, and do not partake of the color. The film surface then acts as a flexible solid, but it is only a few molecules thick, so heat can travel through it quickly by conduction. Whenever a molecule leaves the film in evaporation or one returns in condensation, then another molecule is automatically taken from the film or given up to it respectively. The thickness of the surface film will be a definite value which is determined by the radius of molecular attraction.

Humidity of the air

The fresh air from outdoors enters the air warming conduit of the heat interchanger in an unsaturated condition, and if the temperature of the air is raised 80° F. the relative humidity would be reduced still further if no more moisture entered the air. However, as soon as the air reaches the counterflow chamber, the air takes up moisture, so that, before it leaves, it is nearly saturated.

If the air was near saturation, a little cooling in the room would cause the vapor to condense out in the room. However, when any foreign substance is mixed with water, the vapor tension is lowered. Thus, even though the air has taken up all the moisture it will from the cooled solution, it will still not be saturated, and condensation will not take place in the little cooling that takes place in the room. But when this warm air is cooled still further, say to 10° F. below zero, all the moisture that entered the air is condensed in the air cooling chamber, and so the heat is given up and is not lost. Also, the quantity of water lost from evaporation in the air warming column is recovered in the air cooling column when it is condensed.

The liquid-air heat interchanger has the advantage over other types for building heating because the air is automatically humidified without the usual cost of a humidifier.

Massing of Foam

When the foam is built up into a column, the bubbles are self-supporting, that is, they will not coalesce when massed together. If the glass tube or whatever the chamber wall might be helped to stabilize the foam, it would be necessary to build partitions in the conduit. Such partitions would be a barrier to heat transfer across the wall, and these walls are not traveling with the foam, so they would offer some resistance to the flow.

A test was made in which a column 11 inches in diameter was used, and the results showed the films were fully as stable as the ones in a two inch glass tube. The cross section of the conduit, then, can be made as large as is desired without any partitions inside the chamber to support the foam. A surface that is wet by the solution will have a film of the solution over the entire area, and this film will have less chance to cool than the film between the bubbles. The walls in the column will have such a film on them, and, for this reason, it is an advantage not to need the supporting partitions.

Surface Tension and the Work in Making Foam

Suppose that we have a film stretched on a rectangular frame ABCD, and the sides AB, BC, and CD are fixed, and AD is movable. When the weight of the film is so small it can be neglected, a force, F., must be applied at right angles to AD to keep the film in equilibrium. This force over a unit length where there is only one film is the surface tension of the liquid. Here there is a film on each face, and if d is the length of the side AD the surface tension, T, is

$$T = \frac{F}{2d}$$

The classical way of explaining surface tension is that the molecules inside the liquid are attracted in every possible direction by their neighbors, while those at the surface are attracted only inward and toward each other. This makes the surface layer dense and hard to penetrate, but this force of unbalanced molecular attraction is always perpendicular to the surface. The force of surface tension is tangential to the surface, and the theory of molecular attraction fails to account for it.

Neil H. Williams explains surface tension by the effect of evaporation of molecules from the surface. He uses a mechanical model of a tank with somewhat flexible walls, and fills the tank with steel balls. Then, if the balls are held in position by gravitational attraction, and prevented from coming together by some force such as the bombarding from the heat agitation of molecules, there will be equilibrium. However, if one ball is taken out, there will be no force to hold the adjacent balls out and they will tend to draw together by mutual attraction, and thus fill up the gap. This will tend to draw in the flexible sides, and it is the tendency for a surface to contract which we call surface tension. The gaps to be filled up in a liquid are caused by evaporation, and the magnitude of surface tension depends on the attractive force tending to close up this gap.

The fact that a vertical soap film, when allowed to drain, shows different colors at different places, and is yet in equilibrium, shows that the thickness of the film may vary within wide limits without any substantial change in the surface tension. The surface tension in films of different thicknesses was investigated by Rucker and Reinold. Films over a range of thickness extending from 1350 uu down to the extreme limit were used, and no change in surface tension showed up, although a difference of one-half percent could have been detected. Later, tests show there is some irregularities for extremely thin filsm, but for the average film, the stretching does not change the surface tension.

If in the rectangular frame ABCD, used above, the movable side AD is moved out, a distance x the work done is $Fx = 2\ T\ \overline{AD}\ x$, and this is the surface tension times the increase in film area. The work done against surface tension in forming a bubble is then the surface tension times the area of both the inner and outer films. Because work is required to form a film, we may say that it is at a higher potential energy, and that this surface tension is equivalent to the possession by each unit area of the liquid film of an amount of potential energy numerically equal to the surface tension. Sir Joseph Thomson made a useful application of this by regarding the surface film to be at a higher potential energy rather than having the energy in a strain in the film. In the same way we might consider that lifting a book from the floor to the table was a strain in the ether, but it is better to regard it as being in a state of higher potential energy.

This increase of potential energy will make extra work in blowing the foam, but when the foam is broken at the top of the column, this work appears in its equivalent of heat.

If we have a curved liquid surface in a state of tension, the pressure on the concave side of the surface must be greater than that on the convex. In the foam bubble, there are two films concave to the inclosed air, so the pressure inside will be greater than that outside. Creating this pressure will require work and also heat the air. Imagine a diaphragm across the great circle of an air bubble, and the diaphragm is wet by the film solution. Let P equal the difference of pressure inside, and outside the bubble, and r the radius of the circle. Then the force pressing against the diaphragm, due to this pressure, is

$P \pi r^2$, and this force is balanced by one due to surface tnesion acting around the circumference of the circle, and is equal to $2(2 \pi r) T$, or $4 \pi r T$. The forces are equal, so

$$P \pi r^2 = 4 \pi r T$$

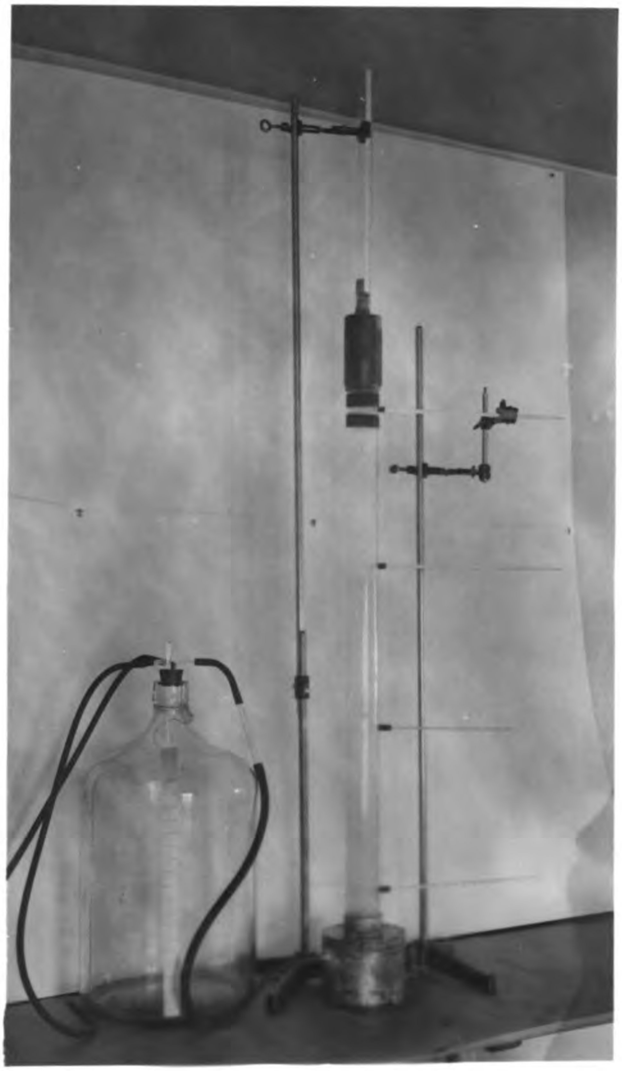
$$P = \frac{4T}{r}$$

At the top of the column this bubble breaks and the air expands to atmospheric pressure, causing a cooling of the air. The expanding of the air causes a cooling and the breaking of the film causes a heating, and these will partly neutralize one another.

The greater part of the work in this heat interchanger is pumping the water to the top of the column and blowing the bubbles under the surface of the liquid. The air will have to be blown under a small head, so that the buoyant force of the bubbles will break them loose, but this head should be as small as possible to reduce the amount of work. The total amount of work to operate this interchanger will be much less than to bubble the air through a column of water and would be approximately the same as the spraying of water in a rising column of air.

The trouble with natural convection currents in the bubbling of air through a column of water will be eliminated here because the sheets of water are very thin, and they move down so rapidly that the slow motion due to natural convection would have no effect. For the same reasons, it would be impossible to set up any harmful amount of turbulence.

The difficulty with dividing the water is also solved by this method, because a drop of water divides at each intersection of the bubbles, and so it spreads itself into very fine sheets in going a short distance. The solution in the heat interchanger can then be distributed by dripping from openings perhaps an inch apart, and yet have a good distribution.



Foam Counterflow Apparatus

PLATE II

Apparatus

The counterflow chamber was a glas tube 92 cm. in length, and 4.6 cm. in diameter. This tube fitted into a metal can at the base which was slightly larger than the tube. This can was perforated with pin-holes through which the air entered the column, and this also was the container for the liquid solution. Around this can was a second metal chamber of 13 cm. diameter. A stop cock was fastened near the bottom to drain off any liquid that ran through the nozzles, and an opening was made at the top where the air was forced in. The air pressure was created by the displacing of air from a large jug in which water was run from the city mains. This jar had a 20,000 c.c. capacity, and it was calibrated along the side, so the volume of air used would be known.

Five holes were cut in the glas tube at 5, 31, 57, 83, and 85 centimeters from the bottom, respectively. In the first four from the bottom, thermometers were fitted and the top one was used to admit the falling liquid. This liquid was supplied from a 120 c.c. burette, which was also calibrated. The bronze wool plug was fitted into the top of the counterflow chamber to break the foam.

Plate No. 2 is a photograph of the final apparatus described above, and the set-up used to obtain the data given below.

Data and Calculations

The first test was that of heating the air and cooling the liquid. The amount of heating liquid was controlled so that the second thermometer from the top was just barely recording the increase in temperature, and in this way the length of the column over which heat was being tranferred could be measured. The thermometers are wet by the liquid and so they have a film of liquid around.them. The temperature readings, then, may be taken as those of the water.

In 22 minutes 15, 100 c.c. of air were passed through the conduit, and 100.1 c.c. of water fell down the column.

If t_1, t_2, t_3, and t_4 are the temperatures at thermometers 1, 2, 3, and 4 from the top respectively, the readings recorded during the test were:

Table I

Time from start	t_1	t_2	t_3	t_4
0 min.	110° F.	83° F.	82° F.	82° F.
4 min.	100	83	82	82
7 min.	100	83	82	82
10 min.	108	83	82	82
13 min.	110	83	82	82
16 min.	108	83	82	82
19 min.	110	83	82	82
22 min.	100	83	82	82
Average	105.8	83	82	82

A steady condition was reached before the readings were started to eliminate any error due to the original cooling of the foam.

The distance between thermometers 1 and 2 is 26 cm., and the diameter of the tube is 4.6 cm.

The diameters of the bubbles ranged from 1 cm. to 2 cm. The readings for the diameters were : .7, 1.0, .5, .3, .8, .7, .8, .7, .7, .5, .3, .2 centimeters, which gives an average of .6 cm.

Volume of tube space

Area $= \pi r^2 = \pi (.3)^2 = 16.62$ sq. cm.

Vol. = area x height $= 16.62 \times 26 = 432.1$ c.c.

Volume of 1 bubble

$V = 4/3\, \pi r^3 = 4/3\, \pi \times .3^3 = .11309$ c.c.

No. of bubbles $= \frac{\text{Vol. of chamber}}{\text{Vol. of 1 bubble}} = \frac{432.1}{.11309} =$ 3820.7 bubbles

Area of 1 bubble

Area $= 4\, \pi r^2 = 4\, \pi\, .3^2 = 1.1309$ sq. cm.

Total surface area $= 1.1309 \times 3820.7 = 4321.0$ sq. cm. of film

$\frac{4321.0}{929.03} =$ 4.651 sq. ft. of film.

100 c.c. water cooled on average 22.8° F.

100 gm. x .0022046 = .22046 lbs.

.22046 x 22.8 = 5.026 B.T.U's transferred in 22 minutes

5.026 x 60/22 = 13.71 B.T.U's transferred in 1 hr.

$\frac{13.71}{4.651} =$ 2.95 B.T.U's transferred per hr. across 1 sq. ft.

In the second test, the air was cooled and the solution heated. The cooling solution was only slightly below room temperature. Eighty cubic centimeters of water and 9000 c.c. of air were passed through the columns, and temperatures read several times with the following results:

Table II

Time from start	t_1	t_2	t_3	t_4
0 min.	66° F.	72° F.	73° F.	73° F.
3.0 min.	64	72	73	73
5.5	68	72	73	73
8.0	66	72	73	73
9.5	64	72	73	73
Average	65.6	72	73	73

Cooling area was same as above = 4.651 sq. ft.

80 gm. x. 0022046 = .17637 lbs. water

.17637 x 6.5 = 1.146 B.T.U's transferred in 9.5 minutes

1.146 x 60/9.5 = 6.86 B.T.U's transferred in 1 hr.

$\frac{6.86}{4.651}$ = 1.47 B.T.U's per sq. ft. per hr.

A second air cooling test was run with the liquid solution nearly to the freezing point. In this test 15,800 c.c. of air and 93 c.c. of water were used. The temperature readings were as follows:

Table III

Time from start	t_1	t_2	t_3	t_4
0 min.	59° F.	67° F.	75° F.	77° F.
1 min	64	69	77	77

Time from start	t_1	t_2	t_3	t_4
3 min.	62° F.	70° F.	77° F.	77° F.
4 min.	63	72	77	77
5 min.	60	70	77	77
6 min.	59	68	76	77
7 min.	62	67	77	77
8 min.	64	69	77	77
9 min.	66	70	77	77
10 min.	62	72	77	77
12 min.	65	70	77	77
14 min.	61	68	77	77
16 min.	59	70	77	77
Average	62	70.6	76.9	77

The cooling area is again 4.651 sq. ft.

93 gms. x .0022046 = .2050 lbs. water

.2050 x 8.6 = 1.763 B.T.U's transferred in 16 minutes

1.763 x 60/16 = 6.62 B.T.U's transferred in 1 hr.

$\frac{6.62}{4.651}$ = 1.44 B.T.U's transferred per sq. ft. per hr.

The purpose of the two air cooling tests was to determine the activity of the liquid-air boundary. Both results were nearly equal, which shows that the boundary is active even at low temperatures. The fact that the apparent rate of the transfer of heat in cooling air is about half what it is in heating air proves that it isn't so much the difference in surface conditions and thicker films as it is that the condensing of vapor increases the load in the air cooling column, while evaporation decreases the load in the other. This is not a loss of efficiency, but only makes the quantity of heat transferred in the two columns unequal.

The results also showed that a considerable quantity of heat can be transferred in a small volume, and that the volume required for the transfer of any given quantity of heat would not depend on the rate of transfer, but rather on the rate of flow of water, through the films and the rapidity with which the bubbles can be broken. As explained before, the films offer little resistance to the flow of water, so the fall is very rapid. The volume, then, used by the designer, will, no doubt, depend on the rate with which the foam can be destroyed.

The temperature gradient between the water and air at the bottom of the column was nearly zero, because the bottom thermometer showed no change in temperature. A test was made to determine the temperature gradient at the top, but the results were not entirely conclusive. Much heat was lost from the walls of the tube, making the measurement difficult; but when a thermometer was raised from the foam into the air, immediately above it, no change could be noted in the temperature. This indicates that there is also a very small temperature gradient at the top.

Conclusion

The present methods of heat transfer pass heat from one body to another at a reasonable rate, only when there is a large temperature gradient or a very large cooling surface. The large cooling surface has resulted in the use of very bulky apparatus and high temperature gradients mean a large thermodynamic loss and low efficiency.

By using a rising foam column of air with liquid falling through the films, the barrier of an intermediate material has been eliminated, there is an active surface between the cooling and the cooled phases; and the liquid has been finely divided.

The structure of foam gives a very large cooling surface in a small volume, making a bulky heat interchanger unnecessary, and tests show that heat is transferred with a very low temperature gradient, less than 1 degree Fahrenheit, thus enabling heat to be transferred with an efficiency which will make the operating acceptable for practical use.

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