PRINCIPLES OF REFRIGERATION – PART 2

By: Paul B. Reed

INTRODUCTION

In discussing the rise in temperature of a liquid to boiling temperature, and the change of a liquid to a vapor, we have considered previously the action of the water and water vapor in an open pan exposed to atmospheric pressure, which is zero pounds per square inch gauge (0 psig) and 14.7 pounds per square inch absolute (14.7 psia). In those cases, the water vapor produced by boiling has been free to fly off into the air.

Now let us see what happens in a boiler, that is, in an insulated, enclosed container of one cubic foot capacity. In its cover we install a pressure gauge and a hand valve. Also, we put in two thermometers of the dial type; one with its bulb in the water in the bottom of the container, to read water temperature and the other with its bulb in the vapor or steam in the space above the water, to read vapor temperature. We put one pound of 70°F water in this closed container but for awhile, we leave the valve open.

At first there is only air inside the container above the water; the gauge reads 0 and both thermometers read 70°F.

Now we turn on the electric heater under the boiler, and begin to add heat to the water. For every Btu of heat we add to the water, it raises one degree in temperature; the water expands a tiny bit in volume, for the molecules move farther apart as they obtain heat energy to enable them to partly overcome their mutual attraction. The thermometer in the water starts to rise fairly rapidly.

The water is not boiling as yet, for its temperature is not up to 212°F. Some of the molecules near the surface get enough energy to jump out of the water, but they are comparatively few. They have lots of room in the space above the water and they bounce off the sides and top of the boiler; a few of them get out through the open valve and some of them bounce back into the water again. The water is evaporating, but it is not boiling.

As we continue to add heat, more and more molecules break away from the water, and the space above the water has more and more molecules flying about in it, some of them getting back into the water. The temperature of the water rises, and so does the temperature of the space above the water, but more slowly.

Finally, the water temperature gets up to 212°F. The temperature of the one pound of water has been raised 142°F (212 - 70) so 142 Btu of heat have been added to the water. Now the temperature of the water remains stationary at 212°F, with the space temperature not far behind. It takes a good while to add enough heat to break down the mutual attraction of any great number of the molecules.

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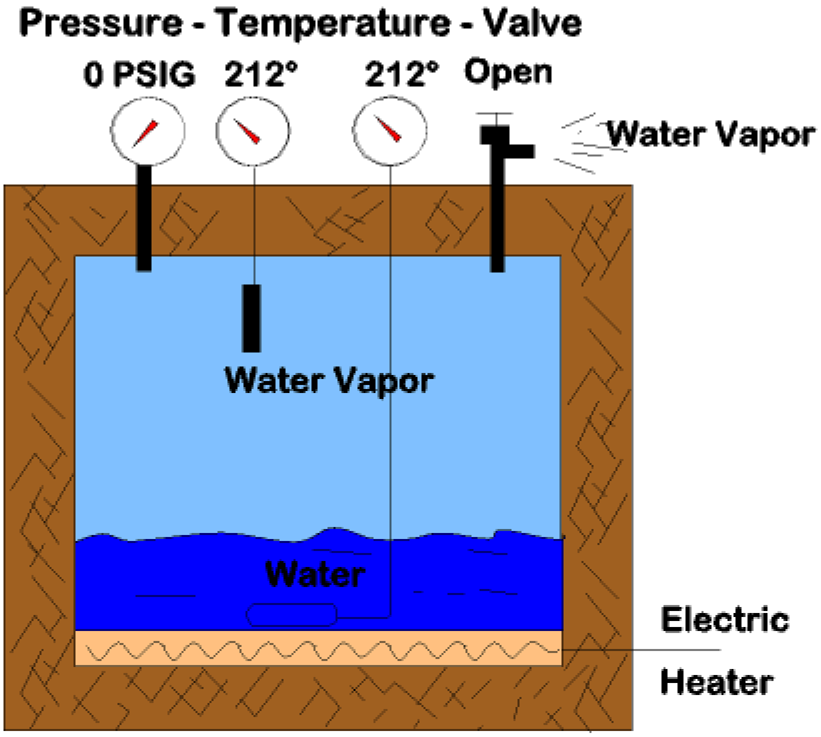

FIGURE 2F25 Water boiling at 212°F at atmospheric pressure.

Before long, however, quite a few of these molecules do get enough heat energy (latent heat of vaporization) to break out of the water.

They go surging out of the surface of the water in large groups or bubbles. There are so many of them that they fill the space above the water with billions of flying molecules moving at a high speed, hundreds of miles per hour. Some of them get out of the boiler, through the open valve, carrying the air in the space along with them. The water is now boiling.

Soon there is so little air left that we can disregard it. The space is now filled with flying molecules of water a long way apart from one another, for they now constitute a vapor or gas. The two thermometers now read 212°F, and we can see the vapor coming out of the valve as steam. The gauge still reads 0, for the valve is still open, so the pressure within the boiler is atmospheric pressure.

SATURATION

We now close the valve, and stop the vapor from leaving the boiler. Now we have a condition called "saturation." Molecules are coming from the water in large numbers, but there are so many in the space above the water that they are bumping into one another and the inside of the boiler so much, that as many are bouncing back into the water as are leaving it.

If we could so exactly regulate the heat under the boiler that we add just as much heat to the water as is lost by radiation from the boiler, we would have a balanced condition, just as many molecules leaving the water as are coming back; thus boiling would continue at 212°F with the gauge continuing to read 0.

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The density of the water vapor is .0373 pounds per cubic foot, the specific volume is 26.8 cubic feet per pound and the total heat in the vapor is 1,150 Btu per pound.

If we turn the heater down a little, there will not be enough heat added to the water to supply the latent heat of vaporization and boiling will soon stop.

TEMPERATURE AND PRESSURE

Let us now turn the heater up, so as to give the water more heat. More molecules are released into the space, many more in fact than can get back to the water. The increased number of molecules means higher density of the water vapor or steam as we may more properly call it, and this means a higher pressure, so the pressure gauge starts to rise. We are adding heat, the water rises in temperature, more molecules are released and they have higher velocities, so the pressure and temperature of the steam also rise.

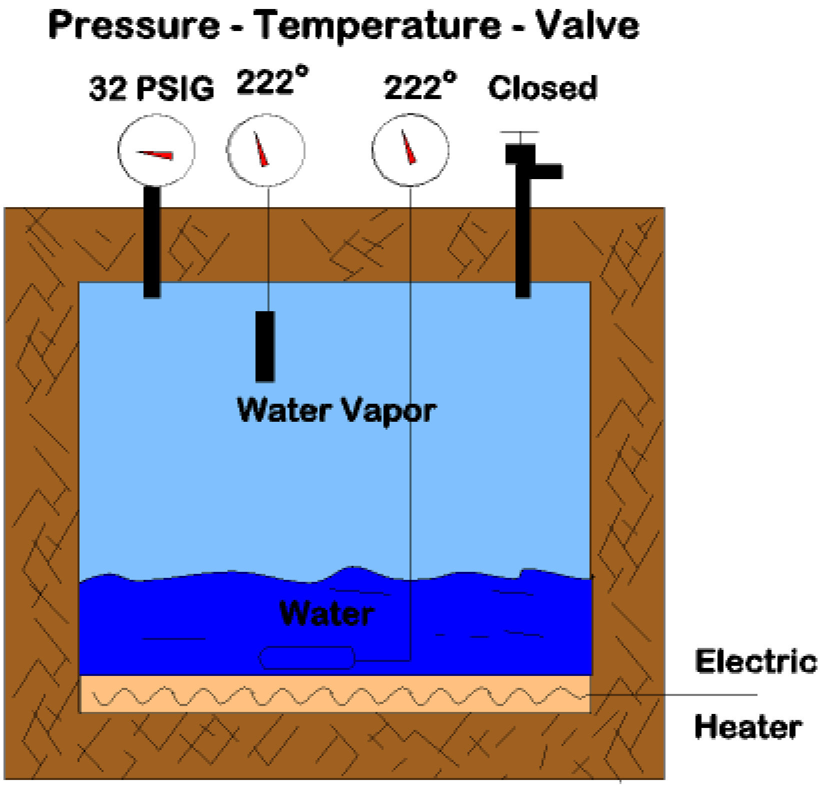

FIGURE 2F26A Water boiling at 222°F and at 3.2 pounds per square inch gauge.

The only thing that goes down is the specific volume (cubic feet per pound of steam); so when the density rises, the specific volume must fall.

By the time that we have continued to add heat to get the water temperature up 10°F to 222°F, the gauge pressure has gone up to 3.2 psig, the density of the vapor has gone up to .045 pounds per cubic foot (specific volume down to 22 cubic feet per pound) and the total heat up to 1,155.2 Btu per pound of vapor.

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As we continue to add heat, the pressure and temperature continue to rise, and more and more of the water is changed into steam, whose density becomes greater and its specific volume less. Also, the total heat of the steam continues to increase, for more heat is being added.

If we continue to add heat, we finally boil away all of the water and we have nothing left but steam in the boiler. In this example of ours with a boiler of one cubic foot capacity and with one pound of water (disregarding the small amount of steam that was lost when the valve was open), now steam, in it, we will run out of water when the density of the steam is one pound per cubic foot, and its specific volume is one cubic foot per pound.

The steam tables, available in handbooks, tell us that this occurs when the temperature of the steam (the water has just disappeared) is slightly over 458°F and the pressure is slightly more than 445 pounds per square inch gauge.

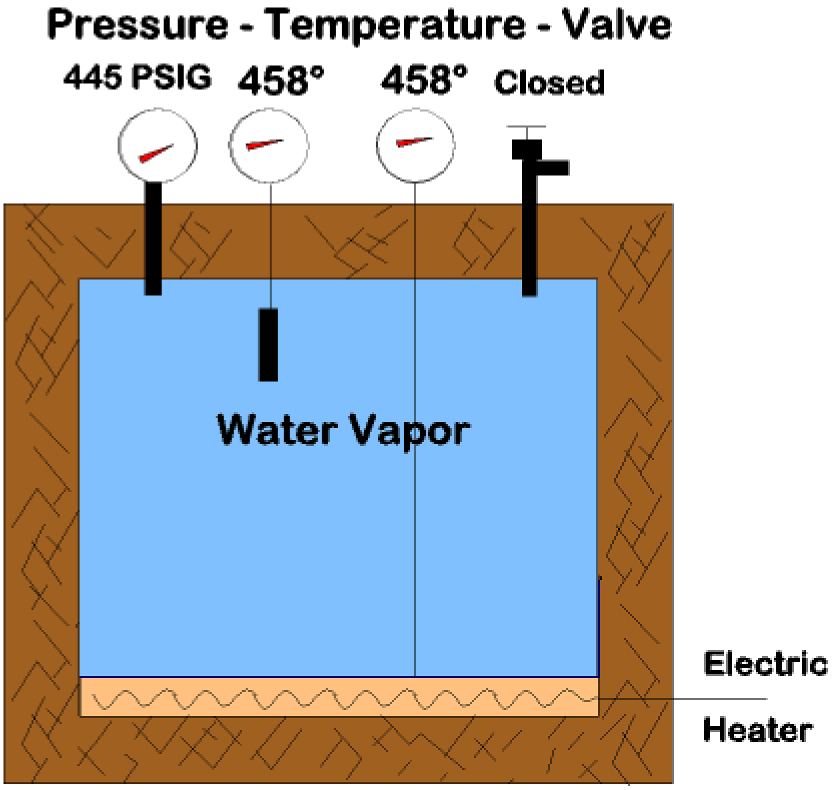

FIGURE 2F26B Condition just when the one pound of water has all been turned to steam.

During all this time between 212°F at 0 psig and 458°F at 445 psig, the steam is saturated. At any temperature and its corresponding pressure, the addition of heat forces more molecules into the space, increasing the density of the steam and its pressure. It took a higher temperature to give the molecules the additional velocity to enable them to get into the denser steam, so the pressure had to go up, too.

If, at any time, we had opened the valve and let some steam out of the boiler, its density would have dropped, so its pressure also would have gone down. With a lower steam density and pressure, it would not have been necessary to have the water so hot, so the temperature of the water and steam would have dropped.

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If we had continued to add heat just as rapidly as before, more steam would have been made in an attempt to make up for the steam lost. If heat were added fast enough, enough steam would be produced to offset the steam lost through the open valve, so the pressure and temperature would stay up where they were when the valve was opened, as long as the water lasted.

In Charles' Law, we said that if the volume were constant, the absolute pressure varied as the absolute temperature. Let us see if that is true in our example. The original pressure was 0 gauge, 14.7 absolute. The original temperature was 212°F or 672°F absolute (212 + 460) and the final temperature or 918°F absolute (458 + 460); so we should be able to find the final pressure as

$$\frac{672^\circ}{918^\circ} = \frac{14.7\,\text{psia}}{\text{Final Pressure}}$$

Cross multiplying

$$672 \times \text{Final Press} = 13{,}494.6$$

$$\text{Final Press} = 20.1\,\text{psia or } 5.4\,\text{psig}$$

But the gauge read 445 psig. What is wrong?

Simply this: Charles' Law, Gay Lussac's Law and Boyle's Law, also the Gas Law using the Gas Constant, do not apply to saturated gases with their liquids present, and in our boiler we had both. Pressures, temperatures, volumes and densities of saturated gases do not follow the gas laws. Their temperatures, pressures, volumes and densities must be taken from "Saturation Tables" in handbooks. These tables are based partly on experimental data and partly on calculation, but the calculations are quite complex and far beyond practical use in the field.

Saturation can occur only when liquid is present with the vapor so that more vapor can be supplied by the liquid if more heat is applied to the liquid. A vapor is also saturated immediately after the liquid has all been boiled away, but at the same temperature and pressure.

We now have one cubic foot of saturated steam at a temperature of 458°F and at a pressure of 445 pounds per square inch gauge; its density is one pound per cubic foot and its specific volume is one cubic foot per pound, but there is no water left.

SUPERHEAT

We still have the electric heater under the boiler, so if we keep it turned on, heat will be added to the steam and its temperature will rise. There is no more water to be turned into steam so neither the volume nor the density of the steam can change; neither of these can increase nor decrease, but its temperature increases.

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Therefore, we have a gas with constant volume, and as the temperature increases, the pressure increases in accordance with Boyle's Law. If we heat this steam on up to 600°F, the pressure should be:

$$\frac{(458^\circ + 460^\circ)}{(600^\circ + 460^\circ)} = \frac{(445 + 14.7)\text{psia}}{\text{Final Pressure}}$$

$$\frac{918^\circ}{1{,}060^\circ} = \frac{459.7\,\text{psia}}{\text{Final Pressure}}$$

Cross multiplying

Final Pressure × 918 = 1,060 × 459.7

Final Pressure × 918 = 487,282

= 530.8 psia (516.1 psig)

If therefore, we continue to heat the steam, after it has run out of water, on up to 600°F from the 458°F saturation temperature, the pressure gauge will rise from 445 pounds (459.7 psia) to 516.1 pounds (530.8 psia).

NOTE:

These figures are not absolutely correct, for the gas laws are not accurate for gas in the saturated region nor slightly above it, but they are sufficiently accurate to illustrate what happens when a saturated vapor is heated after it runs out of liquid, or which is no longer in contact with its liquid.

A saturated vapor heated to a temperature above its saturated temperature is said to be "superheated"; super meaning greater or higher. These two words, saturated and superheated, should be remembered, for they come up time and again in our further study.

VAPOR PRESSURE

We have found that when water at sea level boils at 212°F, the pressure of the saturated water vapor above the water is atmospheric pressure, which is zero pounds per square inch gauge, or 14.7 pounds per square inch absolute. If the water is in an enclosed container, the pressure builds up as the boiling continues, and it becomes necessary to heat the water to a higher temperature in order to get it to boil. If the pressure of the water vapor, or steam as it is also called, builds up to 25 psig, it must be heated to 267°F in order to make it boil; at 50 psig, it must be heated to almost 298°F, etc.

So for each temperature of the water, there is one definite pressure of the vapor above it. This pressure is called its "Vapor Pressure." Sometimes it is called "saturation pressure" or "pressure at saturation."

This is also true for all temperatures below or above 212°F. If the temperature of the water is below 212°F, the vapor pressure of the water is less than atmospheric pressure, but this blanket of water vapor exists just above the surface of the water and it gradually diffuses into the space above the water, whether that space has air in it or not.

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The vapor pressure above water at 200°F is about 11.5 psia, which is about 3.2 pounds per square inch less than 14.7 atmospheric pressure or 6.5 inches of mercury vacuum (3.2 × 2.036). At 150°F the vapor pressure is a little less than 4 psia (about 22-1/2 inches of mercury vacuum); etc., until at 35°F, the vapor pressure of water is only one-tenth (.1) psia, (29.7 in. hg. vac.), which is only one-tenth of a pound per square inch above a perfect vacuum.

Even when the water is frozen into ice, there is still a vapor pressure above the ice, although of course, it is very small. Ice at 32°F has a vapor pressure of .0885 psia (about 29-3/4 inch vacuum).

So liquids have vapor pressures corresponding to their temperatures. Moreover, the vapor pressures are the same for any temperature, whether the liquid is boiling or whether it is merely evaporating at atmospheric pressure. A table of pressures at saturation gives the vapor pressures for that liquid at that temperature.

Water at 212°F, just before it starts to boil, has a vapor pressure of 14.7 psia (atmospheric pressure, or 0 psig) and just after it starts to boil at 212°F it still has the same vapor pressure, although it is then usually called saturation pressure.

Water in an open vessel at 100°F has a vapor pressure of .95 psia (or about a 28 inch mercury vacuum). If we put the 100°F water into an enclosed vessel and draw a 28-inch vacuum on it, it will soon start to boil, and large volumes of water vapor will be boiled off, but the vapor pressure is still the same as when it was evaporating in an open pan, if its temperature is the same.

Vapor pressure is a very important subject to understand and remember, for the whole process of refrigeration depends on it. Also, a knowledge of vapor pressure is necessary to the study of moisture in air, so important in the study of air conditioning.

LIQUIDS OTHER THAN WATER

So far, we have illustrated the principles of saturation and superheat, temperatures, pressures, volumes, densities and heat content by using water in the examples, for water is the most familiar liquid. We could have used any one of many other liquids in our example, for practically all liquids behave just as water does if we apply heat to them.

Of course, other liquids do not boil at the same temperature that water does, nor are the pressures created by boiling other liquids the same as when water boils. The densities, specific volumes and heat contents are not the same either.

Table 2T29 shows the boiling temperatures of a number of liquids at atmospheric pressure (0 psig, 14.7 psia). If at those temperatures we add heat (latent heat of vaporization) the liquid boils and becomes a saturated vapor. Conversely, if we have the saturated vapor of those liquids at those temperatures, and we remove heat from them so that they lose their latent heat of vaporization, the saturated vapors condense into liquids again, but at the same temperature. These boiling points are based on atmospheric pressure, of course.

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T2T29

Table 2T29: Boiling Point of Some Common Materials

Element	°F
Helium	-452
Hydrogen	-422.9
Nitrogen	-320.4
Air	-317.6
Oxygen	-297.2
Ethane	-127.5
Carbon Dioxide	-109.3
Propane	-44.2
R-22	-41.4
Ammonia	-28.0
R-12	-21.6
Methyl Chloride	-10.8
Isobutane	10.3
Sulphur Dioxide	14.0
Butane	31.3
R-114	38.4
R-21	48.0
Ethyl Chloride	54.5
R-11	74.7
Methyl Formate	89.2
Methylene Chloride	103.6
R-113	117.6
Water	212
Turpentine	320
Linseed Oil	549
Glycerin	554
Paraffin	572
Mercury	674.4
Sulphur	832.3
Zinc	1661
Lead	3000
Aluminum	3270
Silver	3635
Tin	4175
Copper	4220

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Gold	5370
Iron	5430
Platinum	8100
Carbon	8700

Thus we see that what we usually call "liquids" are merely materials that have boiling temperatures above the temperatures in which we live. If, in a 70°F room, we place such liquids as "R-11", Methyl Formate, Methylene Chloride, R-113, Ethyl Alcohol, Gasoline, Kerosene, Water, Turpentine, Glycerin or Mercury, they are liquids, for the 70°F is below their boiling temperatures, so they get no heat from the 70°F air. Consequently, they do not boil; but they do evaporate.

If we place such liquids as R-22, Ammonia, Butane, etc., in a 70°F room, they boil, for the 70°F is above their boiling temperatures, and the only way that we can keep them as liquids is to confine them so that the pressure builds up in the container to the saturation pressure corresponding to 70°F and they can no longer boil until the room temperature is raised, or the pressure is partially released.

These liquids that normally boil at temperatures lower than room temperature are called "volatile" liquids, and we use some of them as "refrigerants." We do not have to put a fire under them to cause them to boil; they get heat from the air or from other materials at ordinary temperatures, and so they boil at those temperatures.

Let us now select some liquid that boils at somewhat less than an ordinary room temperature of 70°F. R-21 boils at 48°F at atmospheric pressure, so let us use R-21. So as not to confuse matters by having air in the container or "boiler," we pump a good vacuum on the boiler and then put 1/2 pound (8 ounces) of liquid R-21 into the boiler and close the hand valve. The R-21 will immediately begin to boil as the heat from the 70°F boiler gets to it. At first, the boiler itself will lose heat to the R-21 so fast that the boiler will be chilled to below 70°F, but if we let it sit for quite awhile until the boiler and R-21 come to room temperature, or turn the electric heater on until the dial thermometer in the liquid R-21 reads 70°F, we will find that the gauge will read just under 8-1/2 pounds. If we refer to "saturation" tables for R-21, we will find that the saturation pressure corresponding to 70°F is 8.38 psig.

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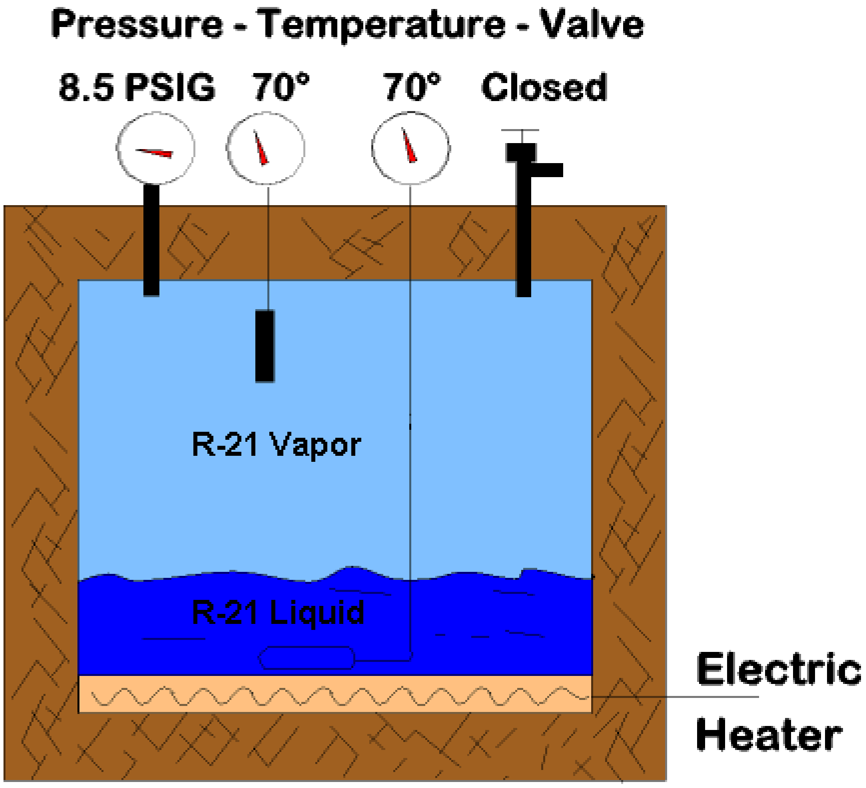

FIGURE 2F29 R-21 in an enclosed boiler at 70°F

Then we turn on the electric heater, so the temperature of the R-21 goes up. At 72°F the pressure is 9.3 psig; at 74°F it is 10-1/4 psig; at 76°F, 11.22 psig; and finally at 78°F, it is 12-1/4 psig. We will note that the pressure has been going up about one pound for each two degrees, or 1/2 pound per square inch for each degree.

But at 80°F we find that the pressure gauge has not gone up appreciably, which indicates that we ran out of liquid at 78°F, and that the heat put into the R-21 from 78°F to 80°F went into superheating the gas. There was actually some increase in pressure, but for 2 degrees it was not enough to show on the gauge. So up to 78°F there was still some liquid, and the R-21 vapor in the boiler was saturated.

Refrigerant tables show other things than just temperatures and pressures. If we look in these saturation tables for R-21, we find that at 78°F the pressure is 12.23 psig and that the density of the saturated vapor is .5021 pounds per cubic foot.

Also, the tables show that the heat in the liquid at 70°F was 26.49 Btu per pound and at 78°F, 28.52 Btu per pound, so the difference of 2.03 is required to heat the liquid from 70°F to 78°F, or 1.01 Btu to heat our 1/2 pound of 70°F liquid to 78°F. Thus the specific heat of the liquid R-21 is 2.03 Btu divided by 8 degrees, or .254 Btu per pound per degree. The specific heat of water is 1.0, so it takes only about 1/4 as much heat to warm one pound of R-21 one degree as it does to warm one pound of water one degree.

The tables also show that the latent heat of vaporization of R-21 at 78°F is 100.22 Btu per pound, so it took 50.11 Btu to boil 1/2 pound of the 78°F liquid and turn it into a saturated vapor at 78°F. The total heat that we must add to 1/2 pound of 70°F liquid R-21 to warm it to 78°F and then boil it, is therefore (50.11 + 1.01) or 51.12 Btu.

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We now have one cubic foot of saturated vapor at 78°F and it weighs 1/2 pound. We have added 51.12 Btu of heat energy to it.

With the electric heater still on, the vapor temperature continues to rise, but we see no perceptible rise in the gauge reading at 80°F, thus indicating that we ran out of liquid at 78°F. Now we are merely heating (superheating) the 78°F saturated vapor and it will now be called superheated vapor.

Let us see what it is at 100°F. According to Charles' Law, the absolute pressure should rise at the same rate as the absolute temperature, so;

$$\frac{78^\circ + 460^\circ}{100^\circ + 460^\circ} = \frac{12.23 + 14.7\,(\text{psia})}{\text{Pressure at } 100^\circ}$$

$$\text{Pressure at } 100^\circ \times 538 = 26.93 \times 560$$

$$\text{Pressure at } 100^\circ = \frac{15{,}080.8}{538}$$

$$= 28.03\,\text{psia or } 13.33\,\text{psig}$$

So in superheating from 78°F to 100°F, the R-21 gas gained only 1.1 psig (13.33 - 12.23) or approximately one-tenth of a pound per square inch per degree, instead of about one-half pound per degree that it gained while it was in a saturated condition with liquid in contact with the saturated vapor.

How much heat did it gain, that is, how much heat was required to superheat the R-21 vapor from 78°F to 100°F? The specific heat of R-21 vapor at that temperature is about .14 Btu per pound per degree. The temperature rise was 100°F - 78°F or 22 degrees, so the heat required to raise the 1/2 pound of 78°F vapor to 100°F superheated gas was approximately:

1/2 × 22 × .14 = 1.54 Btu

The heat that we had to add to the 1/2 pound of liquid R-21 at 70°F to warm it to 78°F and then boil it into a vapor at 78°F was 51.12 Btu. At 100°F the heat in the superheated gas is therefore 51.12 + 1.54 or 52.66 Btu, above the heat in the liquid at 70°F. That is, we added a total of 52.66 Btu to warm one-half pound of liquid R-21 at 70°F to 78°F, boil it, and then superheat it to 100°F.

Suppose that, instead of putting only one-half pound of R-21 into the one cubic foot boiler, we had put one pound in. What would have been the conditions? At first, up to 78°F, the temperature and pressure conditions would have been the same, for there was liquid in the boiler up to 78°F when we had only one-half pound of R-21.

With twice that much R-21, we would also have saturation conditions up to 78°F, so the temperatures and pressures would have been the same, for at saturation conditions with liquid present, the amount of liquid makes no difference in pressures and temperatures.

But with only 1/2 pound of R-21, we ran out of liquid at 78°F; from there on, the heat could only superheat the gas. With one pound of liquid, we do not run out of liquid at 78°F; there is still liquid until we get to 120°F.

How do we know the temperature at which we run out of liquid? Just this: we know that we have one cubic foot of space in the boiler. We also know that we have a pound of R-21. So when we run out of liquid we will have the boiler full of saturated vapor, but no liquid. At that temperature, therefore, the specific volume of the saturated R-21 vapor will be one cubic foot per pound, so we merely look in the saturation tables for R-21 until we find a temperature at which the specific volume of saturated R-21 vapor is 1.00.

From the tables we find that the specific volume is 1.001 for 120°F saturated R-21 vapor. So 120°F is the temperature at which we run out of liquid R-21 in a one cubic foot boiler, cylinder or other enclosed container, holding one pound of R-21.

The saturation table for R-21 at 120°F tells us that the pressure will be 41 pounds per square inch gauge; the heat of the liquid at 120°F is 39.46 Btu per pound, and the total heat in the 120°F saturated vapor immediately after we run out of liquid is 133.53 Btu per pound.

Since the heat of the liquid at 70°F was 26.49 Btu per pound and at 120°F is 39.46 Btu per pound, it took 12.97 Btu (39.46 - 26.49) to heat the pound of liquid from 70°F to 120°F. Since the total heat of the 120°F saturated vapor is 133.53 Btu per pound, and the heat of the liquid is 39.46 Btu per pound, the difference 94.07 Btu (133.53 - 39.46) is the latent heat of vaporization of R-21 at 120°F, and was required to change one pound of 120°F liquid to one pound of 120°F saturated vapor.

We must bear in mind that the 120°F vapor is saturated the same as the 78°F vapor was, but at a higher pressure; and it took more heat to do it. Also, the density of 120°F saturated vapor is greater than the density of 78°F saturated vapor, just double in fact; for there is a pound of vapor in the one cubic foot instead of one-half pound.

The 120°F saturated vapor can be superheated just as the 78°F saturated vapor was. Heat will have to be applied to the boiler in some manner, and the pressure will increase slightly, just as in the case of the 78°F vapor superheated to 100°F.

R-21 BELOW 0 PSIG

We have been dealing with temperatures above the boiling temperature of 48°F of R-21 at atmospheric pressure (which is 0 pounds gauge), so the saturation pressures corresponding to those temperatures have been above zero gauge.

Now let us take our one-cubic-foot boiler, with one pound of R-21 in it, into a walk-in cooler having a temperature of 48°F. As the boiler and the R-21 in it cools, the pressure drops, until when the boiler and R-21 get down to 48°F, the gauge pressure has dropped to zero. At that temperature or below, we could take the cover off the boiler and handle the R-21 just about the same as we would water, oil, or similar liquid. It could sit around in open pails without boiling, but it would evaporate and have a vapor pressure corresponding to its temperature, and the R-21 vapor would diffuse throughout the air in the cooler, along with whatever water vapor might also be in the cooler.

SUMMARY

1. It takes heat to make a liquid boil, and that heat must come from something outside the liquid—a flame, an electric element, hot water, warm air or anything else that has a temperature higher than that of the liquid to be boiled—for heat always flows from a material at a higher temperature to one at a lower temperature.
2. In supplying heat to the boiling liquid, the source of heat loses heat and is itself cooled. If, therefore, we wish to cool some material—hot water, warm air, etc.—we can put it near a liquid that boils at a temperature lower than that of the material to be cooled. In boiling, the liquid takes heat from and thereby cools the material.

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3. All liquids do not boil at the same temperatures at atmospheric pressure, so we can choose a liquid that has a boiling temperature below that of the material to be cooled, and in fact, lower than the temperature to which we wish to cool the material. Such a liquid would "refrigerate" the material, so it is called a "refrigerant." To cool molten iron at 2500°F down to 1800°F, we could place it near zinc which boils at 1661°F, or mercury which boils at 674.4°F, and the 2500°F molten iron would be cooled or refrigerated by the boiling of the zinc at 1661°F or the mercury at 674.4°F. The zinc or mercury would, in that example, be refrigerants.

   To cool oil at 300°F down to 225°F, we can place it in or near water which, boiling at 212°F will cool or refrigerate the oil. In that case, water will be a refrigerant.

   To cool water from 80°F down to 45°F, we can place it near R-114 which boils at 38.4°F and will thus cool the water. In this case, the R-114 is the refrigerant.

   To freeze foods and then sub-cool (chill them below the freezing temperature) down to -20°F, we can place them near ammonia, which boils at -28°F, and the ammonia is the refrigerant.

   If, as is sometimes desirable, we wish to cool liquid R-12 from room temperature down to -30°F, we can do so by placing it near propane, which boils at -44.2°F, or R-22, which boils at -41.4°F. Either the propane or the R-22 will act as the refrigerant, although later, the sub-cooled R-12 at -30°F might also be used as a refrigerant.

   Many other liquids may be used as refrigerants, according to the temperatures to be attained. There are also, of course, other characteristics of refrigerants, such as density, heat content, etc., that must be considered, in addition to their boiling temperatures.

4. By controlling the vapor pressure of the refrigerant, we can obtain a great variety of boiling temperatures of a refrigerant, so that it is not necessary to select a different refrigerant for each temperature that we want to produce, as illustrated in item (3) above.

If we let the vapor pressure build up, the boiling temperature rises. If we pump away the vapor faster than it is being produced, the vapor pressure must drop; so its corresponding boiling temperature drops, also.

For example, in (3) above, we selected R-114 to cool water from 80°F to 45°F, because R-114 boils at 38.4°F at atmospheric pressure. R-12 boils at -21.6°F at atmospheric pressure, but if we do not pump the vapor away as fast as it is boiled off at -21.6°F, the pressure will build up. If we pump it away as fast as it is produced when boiling at 35.5 psig, that is, keep the vapor pressure at 35.5 psig, then the temperature will remain steady at 38.4°F, which is the same temperature that R-114 has when it is boiling at atmospheric pressure (0 psig).

So saturation pressures (vapor pressures at boiling) and their corresponding temperatures go hand-in-hand. If one is changed, the other changes; and if we control one, we also control the other.

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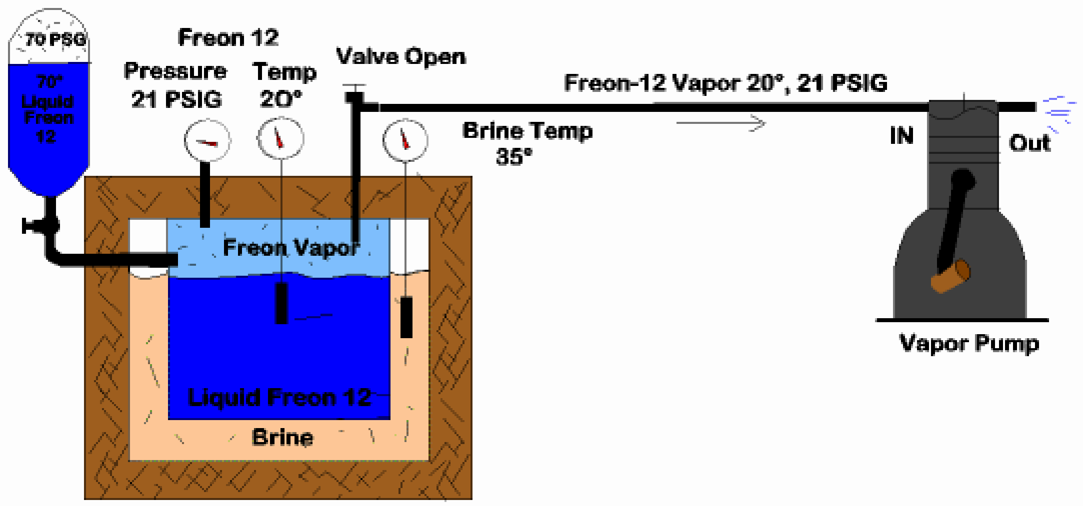


Attaching a suction pump, and a liquid feed tank, with hand valves, to the boiler.

FIGURE 2F32

REMOVING THE SATURATED VAPOR

Now let us make some changes in our boiler. We will leave the gauge, thermometers, and valve, but we will run a pipe from the valve to a pump, so that we can pump the refrigerant vapor away from the boiler. We will drive the pump with a variable-speed motor, so that we can speed up or slow down the pump.

We also provide an inlet to the boiler, and to this we attach another pipe leading from a tank of refrigerant. In the pipe we provide a small hand valve. We could use R-21 as the refrigerant as we did before; but this time, let us use R-12. The tank of R-12 is in the room at 70°F.

The boiling temperature of R-12 at atmospheric pressure is -21.6°F, so we do not need a flame to make it boil. We could use warm water, but water freezes at 32°F or below, so let us use some other liquid that does not freeze until it is cooled to about -40°F. A solution of water and all of the calcium chloride it will dissolve, freezes at about -40°F, so we will surround most of the boiler with this calcium chloride solution. At first, the calcium chloride solution is at a room temperature (70°F) and so is the boiler.

With the inlet hand valve closed but the outlet valve open, we start the pump and pump the air out of the boiler and the gas line. We cannot get all of the air out, but if the pump is very efficient, we can get down to within a small fraction of a pound per square inch of a perfect vacuum, so we will disregard what little air is left.

Now we open the hand valve part way and let a little R-12 into the boiler. As soon as it hits the low vacuum, it will boil, for a 29.9 inch vacuum corresponds to a boiling temperature of R-12 of about -165°, so at first, the temperature of the R-12 vapor will be extremely low.

The temperature of the boiler will not be that low, however, for so little R-12 will boil at that temperature that it cannot cool the boiler down to its temperature. Moreover, as the R-12 comes in, it vaporizes and starts to build up a pressure, and this pressure raises the boiling temperature.

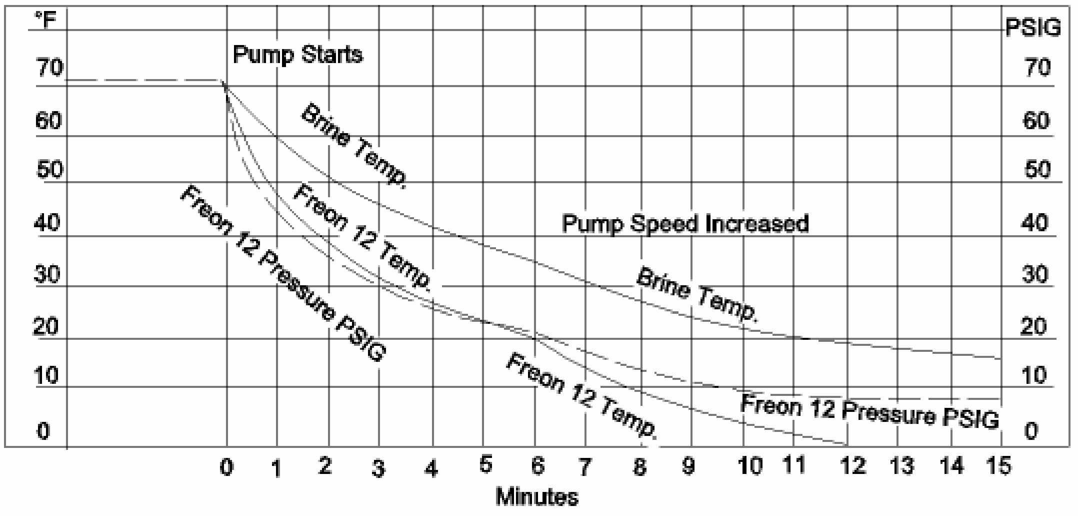
We must let the liquid R-12 in slowly, for as it boils it takes up heat and this heat must come from the boiler and the calcium chloride solution surrounding the boiler, and they will be cooled. If we continue to let in R-12 until the liquid level is up to about 3/4 full, and then shut off the valve and wait awhile, the pressure will finally come to 70.1 psig, the saturation pressure of R-12 corresponding to 70°F. (It is a coincidence that the temperature is 70°F and the pressure about 70 psig; this curiously does not occur anywhere else in the R-12 table of saturation temperature-pressures.)

Now we have the boiler almost full of liquid R-12 at 70°F, with saturated vapor also at 70°F and at a pressure of 70.1 psig.

We start the pump and draw out some of the R-12 vapor. This would tend to reduce the pressure, but it actually doesn't do so at once, for any tendency of the pressure to drop is immediately offset by more vapor being boiled off the liquid, so as to bring the pressure back up. So the pressure remains the same until all of the liquid is used up (that is, boiled into a vapor), as long as the brine around the boiler stays at 70°F and is thus passing heat to the boiler. Then the pressure would start to drop if the pump continued to run.

In order to keep the liquid level at the same height, we open the hand valve slightly and adjust it to supply just enough R-12 to replace the liquid R-12 being boiled and pumped out by the pump. As long as we keep the amount of R-12 vapor pumped out, exactly replaced by new liquid, the liquid level will remain at the same height.

The pressure will be 70.1 psig and the temperature 70°F, provided that the liquid R-12 can get heat from the brine as fast but no faster than it requires to change the liquid R-12 at 70°F to a saturated vapor also at 70°F.



Temperature Curves of the brine and Freon 12.
Dotted line is Freon 12 pressure.

FIGURE 2F33

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TEMPERATURE DIFFERENCE

With both the liquid R-12 and the brine at 70°F, there will be no heat flow from the brine to the liquid R-12. The R-12 must get heat from something. So, if it can get heat nowhere else, it takes it from itself, because at 70°F, R-12 liquid has in it 23.9 Btu per pound (above -40°F).

In boiling, the liquid R-12 therefore cools itself until its temperature gets low enough that there is a wide enough difference in temperature between it and the brine that there is enough heat flow from the brine to the R-12 to supply the heat necessary to cool the liquid from 70°F down to that lower temperature, and then boil it into a vapor.

If we speed up the pump, it removes vapor faster, and more liquid must be let in by the valve to replace the increased amount of R-12 pumped out. If more R-12 is boiled to a vapor, more heat must be supplied to boil it. In order to get this additional heat, there will have to be a greater difference in temperature between the liquid R-12 and the brine, so the temperature of the R-12 liquid goes down a little further, so as to establish a greater difference in temperature between it and the brine.

All this time, heat is passing from the warmer brine to the cooler R-12, so the temperature of the brine gradually becomes lower. Along with this, the temperature of the R-12 must gradually go down also, so as to keep the same temperature difference between the brine and the R-12 that is necessary for enough heat to flow.

As the temperature of the liquid R-12 goes down, its pressure does also, in accordance with the saturation temperature-pressure table.

So at first, the temperature and pressure of the R-12 drop rapidly, say about 8 to 10 degrees, and soon the temperature of the brine starts to drop, and from then on, the temperature of the brine, and the temperature and pressure of the R-12, all three go down at about the same rate. However, the R-12 will be colder than the brine, otherwise no heat can flow from the brine to the R-12.

We will remember too that the density of the saturated R-12 vapor is lower at the lower temperatures and pressures; that is, it weighs less per cubic foot. Therefore, if, at the lower temperature, we run the pump at the same speed, it will pump the same number of cubic feet per minute, but since a cubic foot of vapor at the lower temperatures is not as heavy as at the higher temperatures, the pump will pump fewer pounds of vapor the colder the R-12 and brine get.

If the pump is pumping fewer pounds of vapor at the lower temperature, less vapor can be boiled off, less heat is needed to boil it off, so less heat is taken from the brine and it is therefore cooled more slowly.

We will therefore notice that temperatures and pressure drop more and more slowly. The brine is cooled quickly the first five degrees, a little more slowly the next five degrees and so on; the lower the temperature, the slower is the rate of cooling.

We said that at first the R-12 must drop about 10°F so as to establish a difference wide enough so that enough heat would flow from the brine to the R-12 to vaporize as much vapor as the pump would carry away at that temperature (and density of the vapor). What determines how much the temperature difference must be?

There are three principal factors:

1. The Area Of Contact between the brine and the R-12; that is, the size of the "boiler" holding the R-12 and the height of the R-12 liquid. The greater the area of contact between the liquid R-12 and the brine, the greater the flow of heat between them. Fins on the boiler, extending into the brine, will increase the amount of contact surface area.

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2. The Material of which the boiler is made. If it is a good conductor of heat, such as copper, aluminum and most of the metals, heat flows easily and rapidly. If it is a rather poor conductor or "insulation," such as rubber, crockery, two sheets of metal with an air-space between, or other material that transfers heat slowly, the "rate of heat transfer" is low.

3. The Movement of the brine and of the R-12 liquid. If they move very little, the rate of heat transfer is low. If they can be circulated rapidly, the rate of heat transfer is high. The circulation of the liquids is sometimes called "turbulence."

There are other factors also, such as the nature of the liquids themselves; but the three named are the main ones, and are the ones that we can most easily control. So, for a high rate of heat transfer and a low temperature difference between the boiler and the brine, we want

1. A boiler with a large surface area.
2. A material that is a good conductor.
3. A high velocity or turbulence of the refrigerant and the brine (or air, if the boiler is surrounded by air instead of brine).

Let us now measure what is going on. Let us assume that the bottom of the boiler is one foot square and that the liquid R-12 is one foot deep, and that the brine level is up to the liquid R-12 level. There are therefore five square feet of surface between the liquid refrigerant and the brine.

The pump can pump out one-fifth of a cubic foot per minute (twelve cubic feet per hour). (As the brine gets colder and the suction pressure goes down, the pulp will lose efficiency and will not be able to actually pump one-fifth of a cubic foot per minute, but for our present purpose we will disregard this loss of pump efficiency with a lowered suction pressure).

When the R-12 temperature stands at 70°F and the brine is also at 70°F, we start the pump. It pumps out vapor at the rate of one-fifth cubic foot per minute (abbreviated cfm) or 12 cubic feet per hour. Taking this vapor away will start to reduce the pressure below 70 psig and cause the R-12 to start boiling.

Saturated vapor at 70°F has a density of 2.028 pounds per cubic foot (specific volume of .493 cubic feet per pound), so with the pump pumping at this rate, the weight of the vapor pumped will be 2.028 × 12 (or 12 ÷ .493) or 24-1/3 pounds per hour.

At 70°F, the latent heat of vaporization of R-12 is 61.92 Btu per pound, so if R-12 is being boiled away at the rate of 24-1/3 pounds per hour, heat will be required at the rate of 24-1/3 x 61.92 or 1,506.7 Btu per hour, or approximately 25 Btu per minute.

This rate of cooling will be only momentary, for the removal of heat at the rate of 25 Btu per minute will start to cool the liquid, and the pressure and density of the vapor becomes lower; therefore, the rate of cooling becomes lower. In addition, more and more of the cooling effect must be used in cooling the 70°F entering liquid to the temperature of the cold boiling liquid in the boiler.

However, it does not take long to cool down the liquid R-12, and in the meantime, some heat starts to flow from the brine to the R-12.

Before many minutes have passed, the R-12 is down to 65°F, then 60°F, and on down. In the meantime, R-12 vapor is being taken out, so we must open the hand valve slightly so as to make up for the loss of R-12 and thus keep the level the same.

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Finally, we get down to where the R-12 is at 50°F, its vapor pressure is 46.7 psig, and the brine temperature has dropped 5°F, from 70°F to 65°F. The pump is still pumping out vapor at the rate of one-fifth of a cubic foot per minute or twelve cubic feet per hour, and we have the hand valve open just enough to make up for the loss of R-12 and maintain a constant liquid level.

The density of saturated R-12 vapor at 50°F and 46.7 psig is 1.485 pounds per cubic foot, so R-12 is being vaporized at the rate of 12 × 1.485 or 17.8 pounds per hour. The latent heat of vaporization of R-12 at 50°F is 64.51 Btu per pound, but some of that heat has to be used to cool the liquid R-12 from 70°F, the temperature at which it comes into the boiler, down to 50°F at which it is boiling. From the tables, we find that the heat content of 70°F liquid R-12 (above -40°F) is 23.9 Btu per pound, and the heat of 50°F liquid R-12 (again, above -40°F) is 19.27 Btu per pound. So, the difference, 4.63 Btu per pound, must be used out of the 64.51 Btu per pound to cool the incoming liquid from 70°F to 50°F.

This leaves 59.88 Btu per pound (64.51 - 4.63) as the Net Refrigerating Effect, for it is the part of the latent heat of vaporization that we really get some good out of. (An easier way to find this is to subtract the Heat of the Liquid at 70°F, 23.9 Btu per pound, from the Total Heat of the vapor at 50°F, 83.78 Btu/lb, which gives us the same answer, 59.88 Btu/lb.)

Since the twelve cubic feet of 50°F vapor that we pump per hour weighs 17.8 pounds, and since each pound has a net refrigerating effect (NRE) of 59.88 Btu per pound, the total refrigerating effect of the 17.8 pounds of refrigerant was vaporized is 1,065.86 Btu per hour (17.8 × 59.88).

How much will this cool the brine? Let us assume that we have thirty gallons of brine, or 335 pounds of brine by weight. And let us assume that all of the 1,065.86 Btu per hour will go into cooling the brine.

The specific heat of the brine is .66 Btu per pound—about one-third less than that of water, which is 1.00. The amount of heat that must be removed from 335 pounds to cool it one degree is therefore 221.1 Btu (335 × .66). Since we are cooling at the rate of 1,065.86 Btu per hour, we will be able to cool 335 pounds (thirty gallons) of brine 4.8 degrees (1,065.86 ÷ 221.1) under the conditions given.

As the pump runs, the brine and the R-12 get colder, and saturation pressure keeps going down. Let us see what happens when the brine gets down to 35°F. Assuming the difference in temperature between the brine and the refrigerant is still 15°F, the saturation temperature of the R-12 is now 20°F. We will also assume that the incoming liquid is still 70°F.

We will also assume that the pump is still pumping twelve cubic feet per hour, although it actually will be somewhat less, for the efficiency of the pump will be less at the lower vapor pressure of 21 psig corresponding to 20°F.

The density of 20°F vapor is .8921 pounds per cubic foot, as compared to 1.485 at 50°F, so the vapor now has much less density. Therefore, twelve cubic feet is going to weigh less at 20°F than at 50°F – only a little over one-half as much, in fact. Twelve cubic feet per minute of 20°F vapor will therefore be only 10.7 pounds per hour (12 × .8921) compared to 17.8 pounds per hour at 50°F. This is due solely to the difference in density of the refrigerant vapor.

Let's see what the net refrigerating effect of the refrigerant is now. The total heat of 20°F saturated vapor is 80.5 Btu per pound, and the heat of the 70°F liquid is still 23.9 Btu per pound, so the net refrigerating effect of one pound of R-12 at 20°F saturation with 70°F liquid is 56.6 Btu per pound (80.5 - 23.9).

This NRE is about 3 Btu less than the vapor had at 50°F, which was 59.88 Btu per pound. So we have not only lost refrigerating capacity, because we are not pumping (and boiling) as many pounds per hour, due to a lower vapor density, but the net refrigerating effect has decreased, also.

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At 20°F we are pumping 10.7 pounds of R-12 per hour and it has a net refrigerating effect of 56.6 Btu per pound, so the total refrigeration produced is now 605.6 Btu per hour (56.6 × 10.7) instead of the 1,065.86 Btu per hour we produced at 50°F.

Actually, the specific heat of the brine is very slightly higher at 35°F than it was at 65°F, but it is close enough, so we can still use .66 Btu per pound per degree, and we can still figure on removing 221.1 Btu to cool 335 pounds of brine one degree.

However, we have only 605.6 Btu per hour of refrigeration, so we are able to cool 335 pounds of brine only about 2-3/4 degrees per hour (605.6 ÷ 221.1) instead of 4.8 degrees per hour when the R-12 temperature was 50°F, and the vapor pressure was 46.7 psig.

From this we can see that for the same pump capacity, we can do more refrigeration with a high saturation temperature (and pressure) than at a lower saturation temperature (and pressure). Thus, it pays to keep the refrigerant temperature high, in order to do the maximum amount of refrigeration with the same equipment.

But how can we do this if we are to maintain a certain low temperature in the brine, say 35°F, that we obtain with a 20°F refrigerant? One way, and one of the best and most economical ways, is to reduce the temperature difference between the brine and the boiling R-12. In our examples, we had a 15°F temperature difference.

Suppose that we increase the size of the boiler (its number of square feet) and we agitate the brine and perhaps use copper for the boiler instead of iron. By doing these three things, we increase the rate of heat transfer between the brine and the refrigerant, to where only 7°F difference in temperature between the brine and the boiler are needed to transmit the 221.1 Btu per hour per °F, from the brine to the boiler.

With a 35°F brine, the refrigerant temperature will now be 28°F instead of 20°F. Now the gas will have a density of 1.028 pounds per cubic foot (instead of .892 at 20°F). Pounds of refrigerant pumped per hour will be 12-1/3 (1.028 × 12) instead of 10.7 at 20°F. Net refrigerating effect will be 57.49 instead of 56.6, so the total refrigeration accomplished will be 709 Btu per hour. This will cool 335 pounds of brine (thirty gallons) 3.2°F per hour instead of 2-3/4°F per hour with 20°F refrigerant.

This demonstrates that a low temperature difference between the refrigerant and the brine raises the refrigerant temperature; also increases the capacity of the equipment and increases the rate of cooling the brine, water, air or other material to be cooled. Later, we will find that higher refrigerant temperatures and vapor pressures not only increase capacity, but also allow the pump to operate more efficiently. That is, it can not only produce cooling faster, but also at a lower cost.

We also found that we could reduce the temperature difference by (1) increasing the area of the boiler, (2) using a containment material with better heat conductivity, and (3) increasing the circulation, turbulence, and agitation of the refrigerant and the brine, or other material to be cooled.

PUMPING SUPERHEATED VAPOR

In the preceding examples, we have shown the R-12 vapor going to the pump in a saturated condition, so it has the same density at the pump as it had in the boiler. In actual practice, however, we would not often do this, nor in fact would it be advisable, because of mechanical trouble that would be experienced with the pump.

We remember from Gay Lussac's Law that if the pressure remains the same, the volume of a gas varies as its absolute temperature; that is, with the pressure constant, the volume of the gas rises with increase in temperature, and vice versa.

In Figure 2F37 we have such a condition. The R-12 is boiling at 20°F, the vapor pressure is 21 psig, the density is .8921 pounds per cubic foot, and the specific volume of the vapor is 1.121 cubic feet per pound. Before it gets to the pump, the vapor has warmed up 30°F, superheated from 20°F to 50°F.

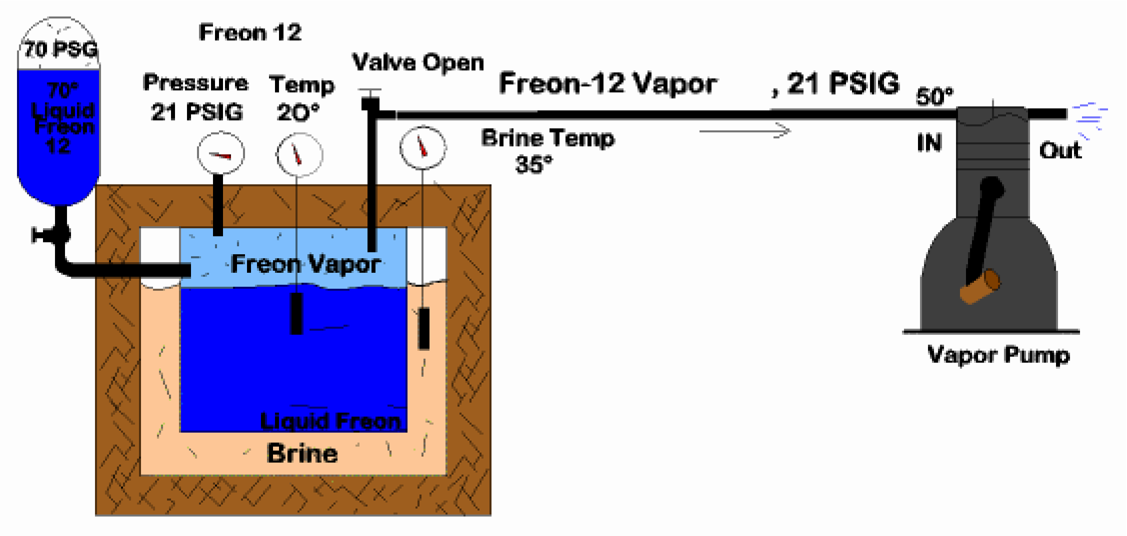

FIGURE 2F37 Freon 12 vapor superheated to 50°F instead of 20°F saturated at the compressor.

The pressure must remain the same, for it is controlled by the temperature of the boiling R-12. If the pressure of the vapor were to increase, the vapor would simply condense back into the liquid Freon. But the pump is taking the vapor away as fast as it is being boiled off, so the pressure at the pump must remain what it was in the boiler. So we can compute the volume of the superheated vapor by:

$$\frac{30^\circ + 460^\circ}{50^\circ + 460^\circ} = \frac{1.121}{\text{Volume at } 50^\circ}$$

$$\begin{aligned}\text{Volume at } 50^\circ &= \frac{510 \times 1.121}{490} \\ &= 1.167 \text{ cubic feet per pound}\end{aligned}$$

The gas laws are not very accurate when we are dealing with vapors that are saturated or almost so. Therefore, our answer of 1.167 cubic feet per pound is not as accurate as the information that we can get from "superheat tables" for R-12. These tables show the specific volumes of R-12 saturated vapors superheated 10°F, 20°F, 30°F, 40°F, etc., above saturation for a number of saturated vapors. If we refer to the table for a saturated gas at 36 psia (which is just a little over the saturation pressure of 35.75 psia for 20°F) we find that the volume of the vapor at 50°F is 1.196 cu ft per pound. Then allowing for the difference between 36 psia and 35.75 psia, we come out with a closer answer of 1.187 instead of 1.167 as the specific volume of 20°F saturated vapor superheated to 50°F.

Our pump is still pumping twelve cubic feet per hour. It is now pumping the superheated gas, whose specific volume is 1.187 cubic feet per pound, instead of the 20°F saturated gas, whose specific volume was 1.121 cu ft per lb. Therefore, the pump will pump only 10.1 pounds per hour (12 ÷ 1.187) instead of 10.7.

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The superheated, 50°F gas will have more heat in it when it reaches the pump than the saturated 20°F vapor had, but it got the extra heat in the line back to the pump, which did not help cool the brine any.

In order to determine the total cooling being done, we will therefore use the same net refrigerating effect as before, 56.6 Btu per pound, for it applies to 20°F R-12 saturations, which is the condition in the boiler. But we must now use the reduced pumping rate of 10.1 pounds per hour, instead of 10.7 pounds per hour of saturated vapor. The total refrigerating capacity will therefore be 571.7 Btu per hour, instead of the 605.6 Btu per hour with 20°F saturated vapor. This is a loss of 34 Btu per hour due to superheating.

This shows the effect of superheating on the volume of gas pumped, and consequently on the capacity in Btu per hour. In actual practice, it is usually necessary to allow some superheating (at least 10 to 15 degrees), and to waste the cooling done by the vapor in superheating in the vapor line to the pump. Sometimes, however, if the superheating is too great, we can save a part of that loss by heat-exchangers, as will be explained later.

COOLING THE R-12 LIQUID TO THE BOILER

In the foregoing examples, we have drawn the refrigerant supplied to the boiler from a supply in a cylinder or other container in the room. Since the room is at 70°F, the liquid R-12 is also at 70°F, and we found from the saturation tables that 70°F R-12 liquid has 23.9 Btu per pound of sensible heat in it. The R-12 liquid had to be cooled down in the boiler, to 50°F, 20°F, or 28°F, in our examples, which means that we must use some of the latent heat of vaporization of the liquid just in cooling the warm liquid down to the boiling temperature. If the liquid R-12 were partly cooled down to the boiling temperature, we could get a much higher net refrigerating effect from the R-12 and therefore a higher capacity.

For example, suppose that we take the cylinder of R-12 out of the 70°F room, to the outside, or to a room that is 40°F, so the liquid reaches the boiler at 40°F, instead of 70°F.

The tables tell us that the heat of liquid R-12 at 40°F is 17 Btu per pound, which is 6.9 Btu per pound less than it is at 70°F.

Going back to the 20°F example, with the 20°F vapor superheated to 50°F, the volume of the 50°F vapor was 1.187 cubic feet per pound and we were pumping twelve cubic feet or 10.1 pounds per hour. But the total heat of the saturated vapor was 80.5 Btu per pound. From this we subtracted the heat of the 70°F liquid of 23.9 Btu per pound, leaving 56.6 Btu per pound as the net refrigerating effect, and that times the 10.1 pounds per hour pumped gave a total refrigerating effect or capacity of 571.7 Btu per hour.

Now, however, we need to subtract only 17 Btu per pound, instead of 23.9, so the net refrigerating effect is now 63.5 Btu per pound. We have not changed the number of pounds per hour pumped, so the total refrigerating capacity is 641.4 Btu per hour (63.5 x 10.1), a gain of 69.7 Btu per hour or over 10%, just by pre-cooling the liquid from 70°F to 40°F. We did not pre-cool the liquid entirely down to 20°F, only a little over half-way, but we made a gain of over 10%.

So we gained back 69.7 Btu per hour by pre-cooling the liquid from 70°F to 40°F, which is about twice what we lost by superheating of the vapor from 20°F to 50°F in the vapor line.

We lost some capacity when the 20°F vapor was superheated to 50°F, because of a loss of density of the vapor. We lost this by heating in the suction line to the pump. That loss of heat to the vapor line just cooled the air around the line and we got no advantage from it.

In pre-cooling the 70°F liquid down to 40°F, we assumed that we had a free source of 40°F air in which to put the R-12 cylinder. Not often would we have this kind of 40°F-room available. So let us try and use the refrigeration lost from superheating in the vapor line, that merely cooled the air and served no useful purpose.

We do this by soldering the line carrying the 70°F liquid to the line carrying the 20°F saturated vapor, as shown in Figure 2F38.

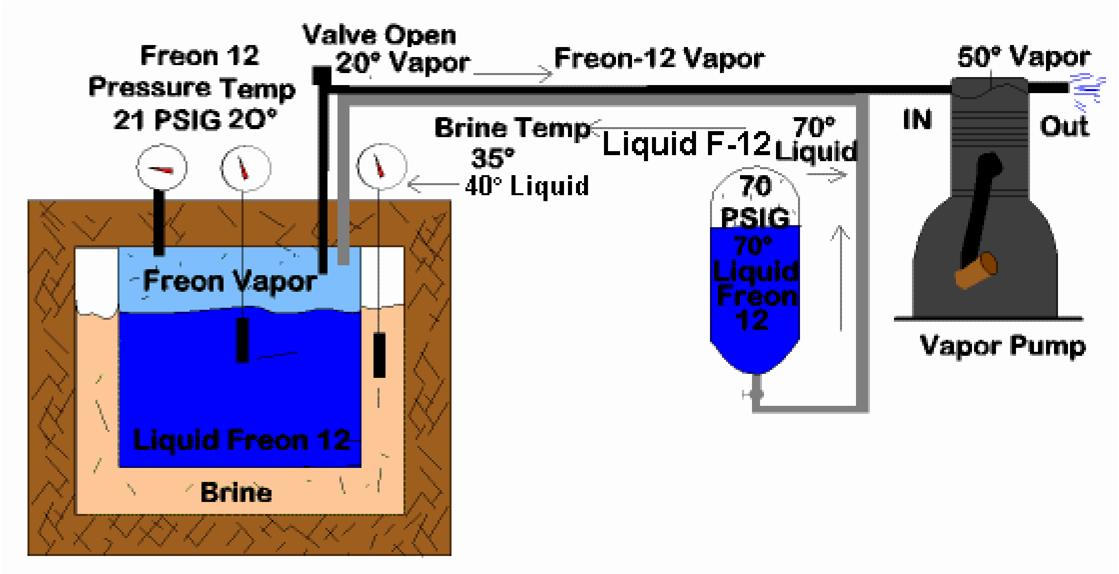

FIGURE 2F38 How vapor is superheated to 50°F and the liquid is cooled to 40°F by heat exchanger.

This is one method of exchanging the heat of the 70°F liquid line with the "cold" of the vapor line, so it is called a "heat exchanger."

So by using the heat exchanger, we came out with a net savings of 35.3 Btu per hour; 69.7 Btu per hour gained in pre-cooling the liquid from 70°F to 40°F, minus 34 Btu per hour lost in superheating the 20°F saturated vapor to 50°F. So the heat exchanger not only kept the vapor from going back to the pump as a saturated vapor, but it also pre-cooled the liquid from 70°F to 40°F, which resulted in a gain in capacity.

SYSTEM CAPACITY BALANCES HEAT LOAD

Why does the liquid R-12 boil at a certain temperature? The pump is running at a fixed speed, and at that speed its displacement is fixed, namely 1/5 of a cubic foot per minute or 12 cubic feet per hour. Therefore we do not change the volume of vapor pumped. How then does the temperature of the boiler change if the volume of vapor does not change?

To find the answer to this, let us go back to the brine around the boiler. In Figure 2F32 we had the brine at 35°F and the R-12 boiling at 20°F. The pressure of the R-12 vapor was 21 psig and its density was .892 pounds per cubic foot. With the pump displacement at 12 cubic feet per hour, the weight of vapor (assuming it to be saturated at and in the pump) was therefore 10.7 pounds per hour.

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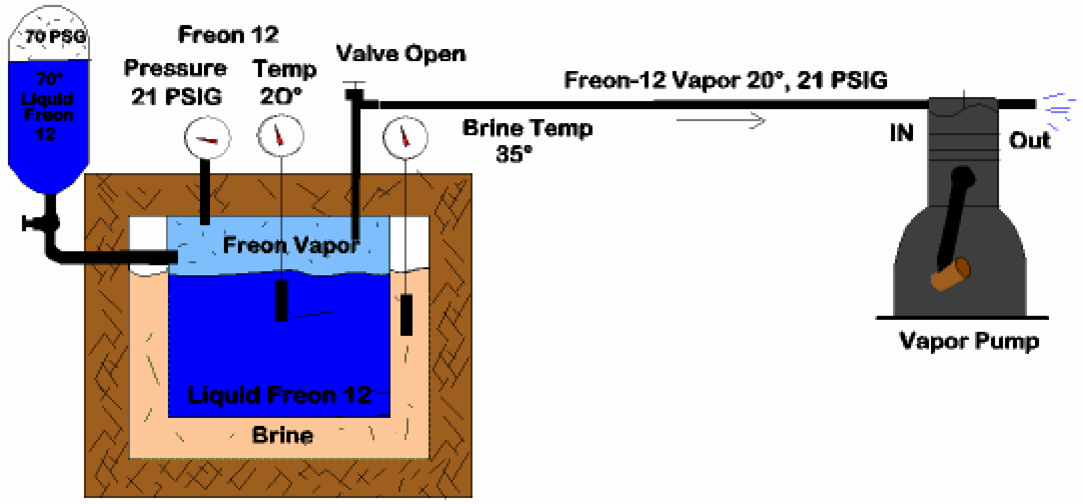

Attaching a suction pump, and a liquid feed tank, with hand valves, to the boiler.

FIGURE 2F32

The latent heat of vaporization of R-12 at 20°F saturation is 67.94 Btu per pound, but from this must be taken the Btu required to cool a pound of the 70°F liquid down to 20°F. The heat of the liquid at 70°F is 23.9 Btu per pound and at 20°F it is 12.55 Btu per pound, so the difference, 11.35 Btu per pound, must be subtracted from 67.94 (the latent heat) to get the net refrigerating effect of 56.6 Btu per pound.

We pumped 10.7 pounds with a net refrigerating effect of 56.6 Btu per pound, so 605.6 Btu of heat were removed from the brine per hour; that is, the brine passed 605.6 Btu of heat to the R-12 per hour. Where did this heat come from? In Figure 2F32, it had to leak through the insulation, for there is no other source of heat shown.

Let us now suppose that we put an electric heater in the brine, and that this heater uses 39 watts. One watt of electricity is equal to 3.412 Btu, so this heater turned on in the brine for one hour will add 133 Btu of heat per hour (39 × 3.412) to the brine. Now the brine will be passing 738.6 Btu per hour to the R-12 (605.6 + 133).

We find that the thermometers in the brine and in the R-12 both start to rise until the brine comes to slightly over 48°F and the R-12 to 30°F, at which point, the temperatures level off and remain constant from then on. The pressure gauge rises from 21 psig to 28.5 psig and stays there. Why do the brine and refrigerant "stabilize" at these temperatures, and at 28.5 psig?

At 30°F saturation, the R-12 has a net refrigerating effect of 57.7 Btu per pound , with the incoming liquid at 70°F. Saturated R-12 vapor at 30°F has a density of 1.065 pounds per cubic foot, so the pump removes, and the boiler evaporates 12.8 pounds of R-12 per hour, and 12.8 x 57.7 = 738.6 Btu per hour.

Therefore, the R-12 at 30°F is removing 738.6 Btu per hour from the brine, which is the amount of heat the brine is giving to the R-12 in the boiler.

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The size of the boiler did not increase, but the brine gave up 738.6 Btu per hour to the R-12, instead of 605.6 Btu per hour, an increase of about 22%. So the temperature difference had to increase about 22%, that is, from 15°F (35°F - 20°F) to a little over 18°F (48°F - 30°F).

To get this additional 22% of cooling effect to match the additional heat from the electric heater, we did not have to do anything except open the hand valve a little wider in order to feed 12.8 pounds of liquid R-12 per hour into the boiler instead of 10.7 pounds per hour.

The boiler got its increased capacity by the rise in temperature difference from 15°F to 18°F, which is in the same proportion as 605.6°F to 738.6°F. If we had used some method of agitating or stirring the brine, we could have increased the rate of heat transfer per square inch of the boiler enough that the temperature difference need not have increased from 15°F to 18°F, and the brine could have been held at 45°F with the R-12 at 30°F.

In fact, if we had agitated the brine even more, we could have increased the rate of heat transfer from the brine to the boiler enough to reduce the temperature difference from 15°F to 10°F and thus have held the brine at 40°F with the R-12 at 30°F.

The pump got its increased capacity, not by running it faster, for its speed and displacement did not change. It got its increased capacity from the increase in density of the saturated R-12 vapor from .892 pounds per cubic foot at 20°F to 1.065 pounds per cubic foot at 30°F. This enabled the pump to remove 12.8 pounds of R-12 per hour at 30°F instead of 10.7 pounds per hour at 20°F.

The R-12 itself gained capacity by its net refrigerating effect increasing from 56.6 Btu per pound at 20°F, to 57.7 Btu per pound at 30°F. Thus there was almost 20% more R-12 evaporated at 30°F than at 20°F, but not 22% more, for the R-12 itself gained in net refrigerating effect enough to make up the total gain of 22% from 20°F to 30°F, that is, from 605.6 to 738.6 Btu per hour.

This illustrates that:

1. The pump gains capacity with increases in suction, vapor temperature and pressure.
2. The R-12 itself gains net refrigerating effect with increases in its boiling temperature. (The net refrigerating effect could have been increased even more, had the 70°F liquid been cooled prior to entering the boiler.)
3. The temperature difference between the boiler (or evaporator as it can also be called) and the brine, must increase if the amount of heat to be removed increases, provided that the rate of heat transfer between the warm brine and the colder boiler remains the same, and in this example we assumed that it did.

Since more R-12 is evaporated per hour, the valve supplying the liquid to the boiler must have greater capacity; that is, it must open wider or have a larger opening, in order to pass the additional R-12 liquid to the boiler. By employing a float on the liquid R-12 in the boiler, the valve could be operated automatically to feed liquid as is needed to keep the liquid level the same.

The outstanding conclusion from this is that the capacity of the system automatically adjusts itself to an increase or decrease in the amount of heat that is passed to it, that is, the capacity of the system rises or falls as required to balance the heat load.

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PRESSURE DROP IN THE SUCTION LINE

In all of the foregoing, we have assumed that the suction line is big enough that it can carry all of the vapor boiled off in the boiler, to the pump. If the tube is too small or too long, or if it has restrictions in it, such as bends or fittings, the vapor cannot flow through it easily. Some of its pressure will be "used up" in pushing the vapor past the restrictions. Therefore, the vapor will have less pressure at the pump end than it has at the inlet end at the boiler. This loss of pressure through the suction line is called "Pressure Drop."

If the vapor leaves the boiler at 20°F saturated, its pressure is 21 psig. If there is a pressure drop of 2 psig in the suction line, the pressure will be only 19 psig at the pump end instead of 21 psig.

The temperature corresponding to 19 psig is 17°F, and the density of the vapor at 17°F is .884 pounds per cubic foot. The displacement of the pump is still 12 cubic feet per hour, so its capacity has been lowered to 10.1 pounds of R-12 per hour, a loss of .6 pound per hour from the 10.7 pounds per hour in a line with no pressure drop.

However, the R-12 is still boiling at 20°F in the boiler, so its net refrigerating effect is still 56.6 Btu per pound, and the cooling capacity is 571.7 Btu per hour (10.1 × 56.6), a loss of over 5%, just because of the 2 psig pressure drop. This reduced capacity is less than the 605.6 Btu per hour heat load, so the boiler and brine will have to warm up some to allow the heat load and the capacity to balance.

This illustrates why it is necessary to avoid pressure drop in the suction line, for it reduces the capacity of the pump and, thereby, the cooling capacity of the entire system.

SALVAGING THE REFRIGERANT

In all of the foregoing, we have boiled the refrigerant by either blowing the vapor out of the boiler or by pumping it out. We have made no mention of what happened to the vapor afterward. We could produce refrigeration in this manner, except that the refrigerant would be wasted, and refrigerant is too expensive to waste.

It has been necessary therefore, to work out some method whereby the vapor could be used again. We could do this if we could get the R-12 back to a liquid again, so we could use it over and over again.