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Use of Heat Pumps in Vapor Absorption Systems

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USE OF HEAT PUMPS IN VAPOR ABSORPTION SYSTEMS

By

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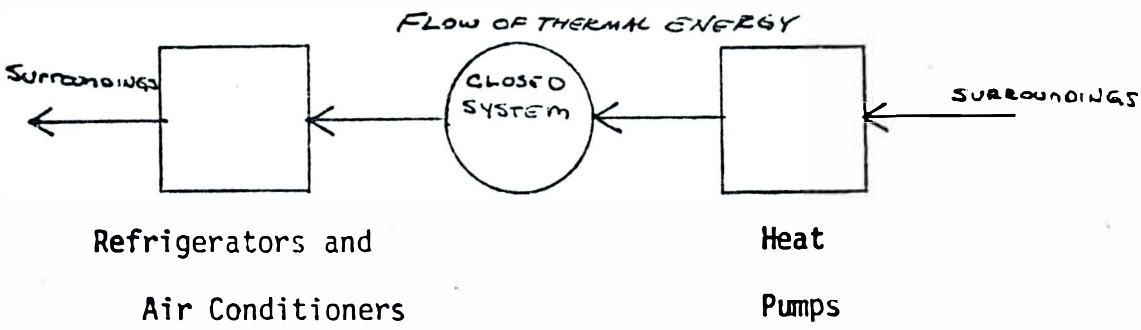
ABSTRACT

The object of this study is to compare the performance of a gas fired dryer and a dryer that utilizes a heat pump for it's source of heat. Since a heat pump was unavailable for testing, ideal models were used to simulate heat pump behavior. Two temperatures and three different humidities were tested. To simulate the different humidity conditions the solvent coater-dryer was used with a water spray device in one of the heating zones. Using a psychometric chart and wet bulb dry bulb measurements the relative humidity was determined. From the data two curves were generated. Using those curves, mass-energy balances, and heat pump literature furnished by Westinghouse[13] the tests show that anywhere from 20% to 50% could be saved on current costs for energy. Though initial installation costs are higher, a payback could be achieved in as little as ten years.

CONTENTS

INTRODUCTION

A heat pump is any device used for the transferring of thermal energy from one substance or medium at one temperature to another substance or medium at a higher temperature. A heat pump consists of a compressor, condenser, throttle or expansion valve, evaporator and working fluid (refrigerant) such as sulfur dioxide, ammonia or freon.[10] Included under this definition would be devices such as air conditioners and refrigerators. With air conditioners and refrigerators thermal energy is a waste product which is removed from a closed system. On the other hand a heat pump will transfer thermal energy into a closed system.



In 1851 Lord Kelvin, the same man who had a temperature scale named after him, described a "reverse heat cycle" in his paper, "The Dynamic Theory of Heat". In this paper Lord Kelvin wrote about being able to transfer heat as if it were something tangible. Instead of heat moving toward equalibrium, the paper mentioned increasing the differential temperature.

The term "air conditioning" was created in 1907 by Stuart W. Cramer. Mr. Cramer suggested that steam be added to the ambient air of a textile mill to raise the humidity. The higher humidity slowed the drying rate of the fibers. Not long after this, in 1911, Willis Carrier (a name still famous in the air modification field) laid the foundation for air conditioning in scientific terms.

Refrigerators have been in use since 1805, but in those old models air was used as a working "fluid" in the compressor. It was not until 1856 that the first refrigerator using vapor-compression was introduced. Heat pumps were not introduced until 1930. A heat pump can be used to transfer thermal energy that exists in a medium, generally outside air, into a smaller volume.[7,10]

The ratio of energy input to output or C.O.P. ranges in the area of 1:6 to 1:7.[1] Although the efficiency of a heat pump is largely dependent on the differential temperature between the mediums, normally one BTU will transfer three to four BTU's. In the 1940's because of the limited availability of fossil fuels and an abundance of hydroelectric power, Switzerland found heat pumps to be economically advantageous. The advent of the oil embargo and rapidly climbing fuel costs have caused many new homes to have a heat pump installed rather than the conventional oil or gas furnace. These units have been so cost effective that the initial costs were recovered in as little as five to seven years. Some designs have added two or more compressors in series. This will permit lower evaporator or higher condenser

temperatures. Compound heat pumps as these units are called, have been designed to work against a temperature gradient as high as 90°F. It is evident that industrial temperatures can be reached with compound pumps.

The heart of any heat pump is the compressor. There are four main types of compressors; reciprocating, centrifugal, helical and axial flow fans. The reciprocating type is found most often and can have a capacity as high as 250 tons of refrigeration. Because it is a positive displacement system, it can maintain high discharge heat resulting in high condensing temperatures under low load conditions. Centrifugal compressors will have ranges from 100 to 10,000 tons. Because of the costs involved with this type of unit, their applications are limited to installations needing refrigeration in excess of 200 tons. The helical and axial flow compressors offer a middle ground. The capacities range from 10 to over 1,000 tons. Since they are positive displacement types, like the reciprocating compressor, they can operate at high heads and reduced loads. Since they use a rotating piece of machinery, they like the centrifugal compressor, run smoother.

By and large the heat pump is used in most cases to heat and cool buildings. The availability of close heat sinks or sources have made the heat pump a popular alternative to the conventional furnace-boiler system. As far as the use of heat pumps in industrial applications, their use has been limited. Due to high temperatures used, heat pumps have not been as successful in industrial applications.

One industrial application in which heat pumps are already being tested is in the drying of grain. Grain Processing Corporation has tested a system, and the results look promising. Even in this area the heat of vaporization is recovered, the small losses incurred are made up by the compressor. When drying grain, it is important to keep the temperature as low as possible so as not to "cook" the grain. Because of the low temperatures, low humidity is necessary.

Background Discussion

Temperature

The most important aspect of drying in any situation is the driving force associated with temperature. Since:

$$q/A = K(\Delta T)/B \quad \text{or} \quad BTU/Hr\ ft^2 = K(\Delta T)/B,$$ [9]

the greater the temperature gradient the higher the transfer of energy between mediums. By increasing the temperature of the carrier medium there will be an increased tendency for a transfer of heat from the air into the coated paper. As the heat is transferred to the coated paper, the water in the coating will begin to vaporize.

Heat of Vaporization

To vaporize water a large amount of energy is converted. ? Each pound of water that changes phase requires approximately 1000 BTU's. If the system is closed, the temperature of the surrounding air is significantly lowered. To vaporize one pound of water 100 lbs. of air would have to lose about 42F°. In conventional dryer systems this vaporized water and air is exhausted, and the energy used to vaporize the water (1000 BTU's per pound) and heat the air is lost. If this energy could be recovered by condensing the water, then a majority of the energy in this process could be recycled.[4]

Relative Humidity

At temperatures in excess of 300°F relative humidity plays a small part in controlling the rate of evaporation. As the level of temperature declines however, the relative

humidity can be changed a great deal by small changes in the water content of the air. At 200°F it becomes so critical that a change of one mole of water in 13.4 moles of air will cause a change of 10% relative humidity. The lower the operational temperature of the dryer, the more important the relative humidity becomes.

Experimental Procedure

Equipment:

Dryer. The dryer used was an arch type dryer, approximately 20 feet long with 3" aluminum rolls on 21" centers. The dryer is supported by the coater and laminator framework. The dryer rolls are direct driven from the laminator drive motor. A manual threading chain is provided and all roll bearings are outside the heated area.

The air dryer is designed with two independent heating zones and each zone has separate controls for nozzle velocity, supply air temperature, and exhaust air flow. The air impingement nozzle velocity in each zone has a range of 3000 to 8000 FPM with a 12,000 FPM maximum in Zone 2 and a supply air temperature range of 150° to 500°F in Zone 1, and from 150° to 800°F in Zone 2.

Fans. For each heating zone there is a centrifugal type fan to supply 3100 cfm. Each fan is driven by a 7-1/2 HP motor. There is one centrifugal type exhaust fan to exhaust 7000 cfm. This fan is driven by a 10 HP motor.

Burners. There are two gas burners with safetys to prevent gas buildup. The Zone 1 burner sized for duty at a temperature of 600°F will deliver 1,200,000 BTU/hour. The Zone 2 burner is sized for duty at 800°F and will deliver 2,000,000 BTU/hour. A great deal of difficulty throughout the course of the experiment was caused by the Zone 1 burner.

Supply Headers and Nozzles. The supply headers consist of direct impingement nozzles to achieve maximum drying efficiency. The supply headers are individually controlled by automatic air operated dampers. The exhaust is controlled by manual dampers. The supply nozzles are the slotted type, covering the full width of the web. The nozzle opening is manually adjustable across the full width. Nozzle construction is of black steel.

Humidity Adjustment. Humidity adjustment was done in Zone 1 with a spray header misting water over the burner. Care was taken not to drown out the flame. By using a pair of thermocouples modified for wet bulb dry bulb measurements and a psychometric chart, the relative humidity can be determined.[2]

Procedure

Dry samples were taken to determine basis weight of paper stock. At each relative humidity and temperature tested, a sample was taken before and after the drying phase. This allowed me to determine the amount of water on the sheet and how much is evaporated by the dryer.

The temperature ranges used were 150°F and 200°F. The relative humidity ranges at 150°F were 10%, 30%, 50%. At 200°F the ranges were 20%, 30%, 50%. To obtain these levels a chart of required wet bulb dry bulb readings were produced.

Temp.	R.H.	Wet Readings	Dry Readings
150°F	10%	70°F	150°F
150°F	30%	105°F	150°F
150°F	50%	123°F	150°F
200°F	20%	132°F	200°F
200°F	30%	146°F	200°F
200°F	50%	167°F	200°F

These values were obtained using formulas found in the ASHRAE Fundamentals Handbook, Reference on Psychrometrics.

After the dryer had stabilized at a given temperature, water was used to adjust the wet bulb. After two minutes, if the readings were stabilized, samples were taken as specified. They were bagged, tagged, and taken to a lab for evaluation. The samples were then kept overnight or until they were acclimatized. Weights were taken a second

time; the difference will be equal to the water contained on the sample. The second weight will also tell me what size the sample is so as to determine the weight of water that was applied. Given what was applied, what was removed and the paper speed, I can determine the rate of evaporation.

RESULTS

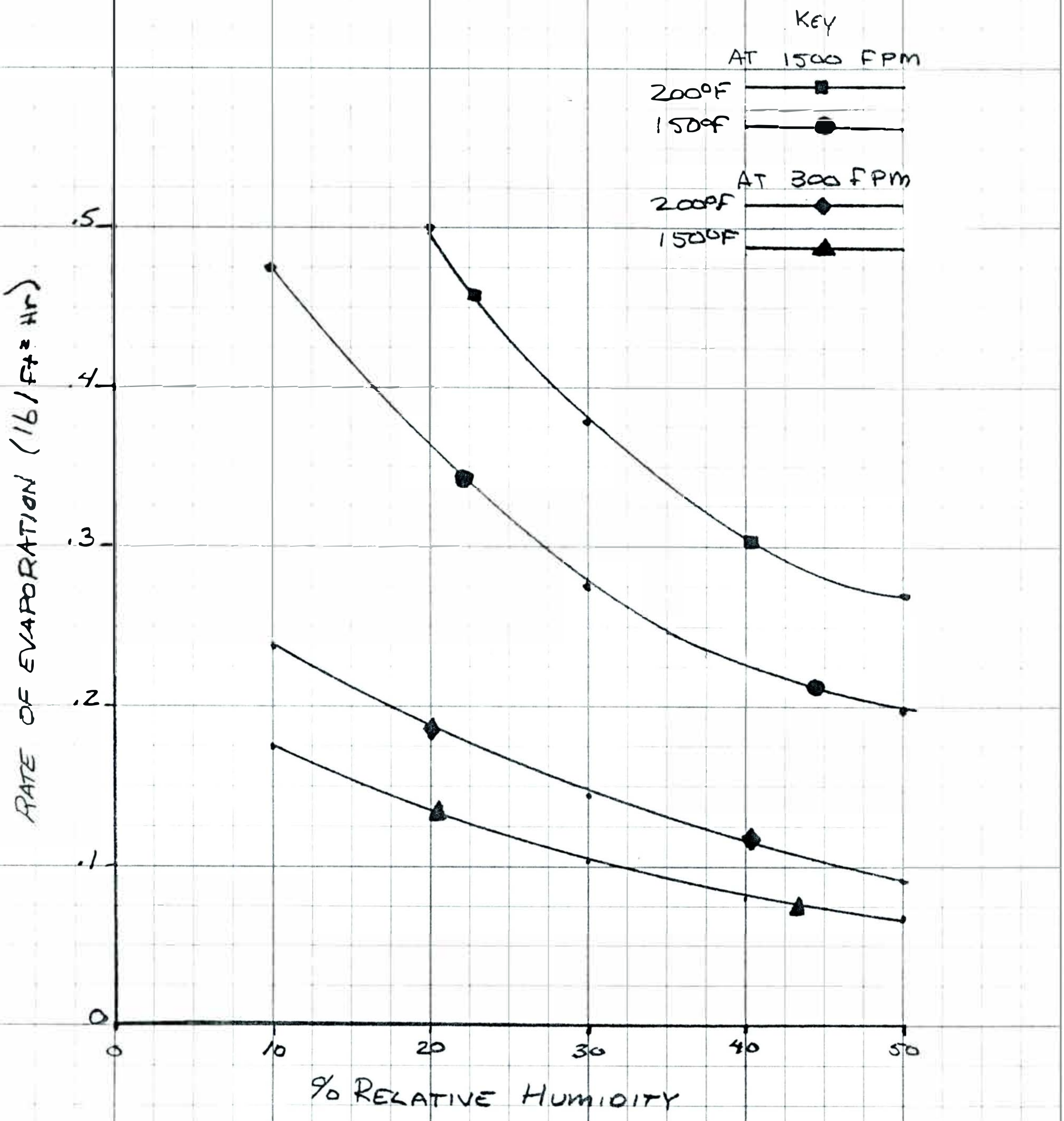
I found that as the relative humidity was decreased at a given temperature, the ability of the air to pick up moisture was increased. A table of the results follows:

Rate of Evaporation

($lbs/ft^2/hr$)

Relative Humidity	150°F	200°F
10%	.473	--
20%	--	.502
30%	.258	.367
50%	.203	.261

(A graph of the results is included on the following page.)



THE DATA POINTS WERE AT 10-30-50 % RELATIVE HUMIDITY EXCEPT FOR THE 200°F 1500 FPM LINE WERE THEY ARE AT 20-30-50 % RELATIVE HUMIDITY

CONCLUSIONS

It is known that at high temperatures relative humidity is an insignificant factor in the rate of evaporation. This is due to the large vapor capacity of hot air. When the temperature of the drying medium reaches 200^oF, however, a 10 lb change in the water vapor content will change the relative humidity 10%, in 100 lbs of air. One way to avoid the slow drying rates with the low temperature air is to use high velocity impingement dryers. With high velocities energy can be transferred as this is similar to the windchill factor we experience. The temperature doesn't change, but it seems like it does. The high volumes of air increase the energy available for heat transfer.

I found that at lower temperatures effective drying can still take place. The amount of water evaporated is smaller, and the rate of evaporation lower than with the higher temperatures, but in special applications, heat pumps may prove even more effective than gas dryers. The experimental results were applied to models of a gas dryer and a heat pump (see Appendix 1). Using performance ratings from Westinghouse literature and assuming 100% conversion of natural gas to carbon dioxide and water vapor, the cost for operating a gas dryer will vary from $15,670/year to $45,000/year, using a heat pump would cost $11,700. The minimum savings in energy costs would be $3,970/year, a 25% savings. Assuming the cost of gas burners to be small compared to the total equipment cost, the real difference

in cost would be the heat pump itself. This difference is equal to $80,000. If energy costs for fossil fuels are inflated by 20 percent per year, and electricity is inflated by 10 percent per year (a conservative guess, though the ratios should remain the same) the average yearly cost for energy will differ by $22,000/year over ten years (see Appendix 1). Payback will be achieved in 6.7 years. Federal tax breaks were not considered but an additional savings would be obtained that would shorten the payback time.

One of the future applications may be the drying of heat sensitive coatings. The current method is to use a solvent that has a low temperature of vaporization. The problems associated with this method of drying are threefold. First and foremost, the evaporating solvent in most cases is explosive; water vapor is not. Secondly, the environmental problems associated with solvent vapors cause a great deal of money to be spent on equipment to deal with the effluent; water vapor is ecologically passive. Lastly, the cost of the solvent could be a factor. If it can't be easily recovered, it could lead to a product pricing itself out of the market.

These systems may even find their way into commercial coating applications. Indications from the literature and Westinghouse point toward a new generation of heat pumps in the wings. With the costs of energy rising (especially energy that is hydrocarbon in nature). These new heating devices may find their way into use in the next ten to fifteen years.

The biggest plus with the heat pump system is the ability to recover the heat of vaporization used in a process. In applications where water must be removed by evaporation in most present day dryers, the vaporized water is exhausted to the atmosphere. Some attempts to use this source of heat have been tried but not to the success that a heat pump could achieve. Since heat pumps are basically refrigerators in reverse, most repairs can be performed by in-house maintenance crews.

The cost of installation may prove to be the barrier that prevents widespread acceptance of these heating systems. The initial costs are higher with heat pumps but the annual costs are lower; ranging from 20% to 50% less (see Appendix 1). A heat pump that would do the work outlined would have to be about 113 tons of refrigeration in size. With rising costs and a depletion of our natural resources a payback time could be achieved in as little as seven years.

The age of inexpensive energy is gone. This, coupled with the problems industrial plants faced several winters ago, should make the efficient use of energy everyone's top priority. I feel that this study shows part of the great potential the heat pump offers us.

Recommendations

First and foremost I would suggest that a heat pump be made available for in-depth study. It should be placed in line with a gas fired dryer. Monitors should be placed on the heat pump to determine the electrical energy used and on the gas burners to determine natural gas consumption. This will give real world values to complement my study. To help simplify matters a humidity testing device that would monitor dew point of the gas, or measure the concentration of water in air directly would be needed. This would narrow the range of possible error by providing a more exact means of controlling humidity.

Tax consequences is a consideration that might also be followed up. Savings provided by tax deductions or accelerated depreciation were not considered in this study, but any additional gains would shorten the payback time.

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APPENDIX 1

DRYER CONSTRAINTS

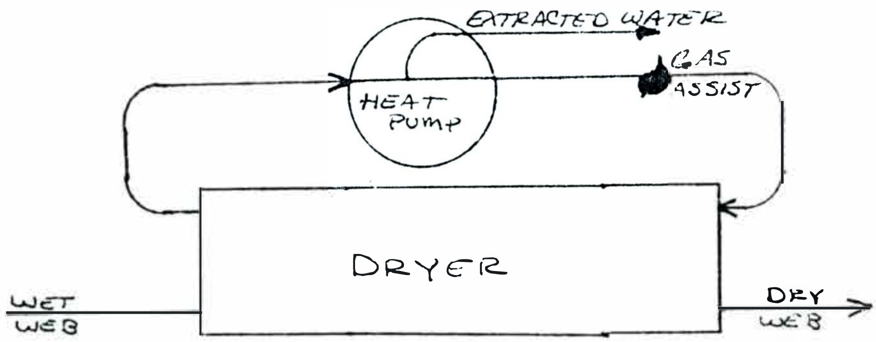
Dryer Bed Size	3 ft. x 50 ft.
Dryer Exhaust	10% of its Volume per minute
Make-up Air Temp.	70^{o} F
Coating Temperature	70^{o} F
Paper Feed	1000 ft^2/min. (3000 ft^2/min. at 400^{o}F)
Coat Weight	10 lbs (50% solids)
Water added/1000 ft^2	10 lbs.
Dryer Year	200 - 24 hour days

Heat loss to radiation was considered constant in all three cases.

STP conditions were assumed for all mass and energy balances.

Dryer 200^{o} (Exit Air)

Since this dryer will use a heat pump as the major heat source recovering the heat of vaporization, we will be more concerned with the heat transferred per minute. Since no system is perfect, a small gas burner will be used to assist in achieving the necessary levels of heat required.



Since the differential temperature is smaller than at 300^{o}F (or 149^{o}C) it will take a dryer bed (according to test data) 1.6 times as large assuming 10% relative humidity. If all other dimensions are increased by that same factor, then the carrying medium would have to have a volumne of 4800 cf. If it took one minute for the air to pass through the system, then:

4800 scf/(359 scf/lb-mole) = 13.37 lb. moles (unless stated mole = lb-mole)

Partial pressure of water in saturated air at 80^{o}F is 1.03 in. Hg.

1.03 in/29.92 in = .0345 (3.45% water)

13.37 moles x .0345 = .461 moles water

Assuming that the humidity caused by the gas burner assist is negligible, then the dryer humidity at 200°F would be:

.461 moles water/13.37 moles air = .0345 or 3.5%

.0345 x 29.92 in. = 1.03 in.

Since: Pa/Ps x 100 = Relative Humidity

1.03 in/23.467 in. x 100 = 4.4% Relative Humidity

With the added water removed from the coating

10 lbs H_2O/1000 Running Feet = .555 moles

(.461 moles + .555 moles)/13.37 moles air = .077

29.92 in. x .077 = 2.308 in.

2.308 in/23.467 in. x 100 = 9.8% 10% Relative Humidity

With this information, at an Exit Temperature of 200°F:

Energy in Air:

(12.91 moles)(6.96 BTU/mole°F)(200°F - 70°F) = 11,227BTU

Energy in Water Vapor:

18.3 lbs (1146 - 38 BTU/lb) = 20276 BTU

Total at Exit = 32,373 BTU

To provide the necessary energy to vaporize 10 lbs of H_2O from 70°F to 200°F the entrance air must be 316°F.

Energy in Air:

(12.91 mole)(6.96 BTU/mole°F)(316°F - 70°F) = 22104 BTU

Energy in Water Vapor:

8.3 lbs (1184 - 38 BTU/lb) = 9512 BTU

Total at Entrance = 31616 BTU

At the Evaporator the Air-Vapor Mix in Cooled to 80°F

12.91 moles (6.96 BTU/mole °F)(80°F - 70°F) = 931 BTU

8.3 lbs (1096 - 38 BTU/lb) = 8.781 BTU

10.0 lbs (80°F - 70°F)(1 BTU/lb°F) = 100 BTU

Total Energy Extracted from Moist Air Stream:

32,373 -9812 = 22,561 BTU/min.

At the Condensing End

22,561 BTU + 8,781 BTU + 931 BTU = 32,273 BTU

Gas Make-Up Heat = 100 BTU/min. or 28.8 x 10^6 BTU/Year

28.8 x 10^6 BTU/Year/345,168 BTU/mole = 83.4 moles

83.4 moles, 29,954 ft^3 or 30 mcf (mcf = 1000 cf)

30 mcf x $4.10/mcf = $123.00/Year Make-up (or a waste heat source!)

The heat pump since it would transfer 22,560 BTU/min or 1,353,600 BTU/hr and having a C.O.P. of 4 (4 is very conservative as some heat pumps range to 8 and 9) would need a power input of 338,400 BTU. The kilowatt equivalent would be 99 kw.

The cost for Energy would be:

476,340 kwh/year x .0243¢/kwh = $11,575

Total Cost $123. + $11,575 = $11,698 or $11,700

Dryer 300^{o}F (Gas Fired)

Total Cubic Volume 3,000 scf

Exhaust 300 scf (300 ft^3/359 ft^3 = .835 moles)

.555 moles H_2O + .835 moles = 1.39 moles/min. Exhaust

.555/1.39 x 100 = 40% Exhaust is Water.

At 300^{o} Pressure at Saturation is 136 ins.

29.92 in. x .40 = 11.97 in. pressure of water

11.97 in./135 in. x 100 = 8.8% relative humidity

Energy used for Water Removal (From CE Steam Tables, Reference #5)

(1180 BTU's)(10 lbs/min.) = 11,420 BTU's/min.

11,420 BTU's/min. x 60 min/hr. = 685,200 BTU's/hr.

685,200 BTU's/hr x 24 hr/day = 16.444 x 10^6 BTU's/day

16.4 x 10^6 BTU/day x 200 days/year = 3,289 x 10^9 BTU's/year

Energy used for Make-up Air (From Conservation of Mass & Energy, Reference #14)

(6.96 BTU/mole^{o}F) or (.24 BTU/lb^{o}F)

.835 moles (6.96 BTU/mole)(300^{o}F = 70^{o}F) = 1337 BTU/min.

1337 BTU/min x 60 min/hr. x 24 hr/day = 1.925 x 10^6 BTU/day

1.925 x 10^6 x 200 days/year = 3.85 x 10^8 BTU/year

BTU USE PER DAY = 18.369 x 10^6 BTU/day

BTU USE PER YEAR = 3.694 x 10^6 BTU/year

Natural Gas Used (345,168 BTU/mole or 359 ft^3)

For 1 day 18.369 x 10^6/345,168 BTU/mole = 53.2 moles/day

For 1 year 53.2 moles x 200 = 10,644 moles/year

10,644 x 359 ft^3/mole x $\frac{mcf}{1000\ ft^3}$ x \$4.10 mcf = \$15,670/year

Dryer $400^{o}F$ (Gas Fired)

Total Cubic Volume 3000 ft^3

Exhaust 300 ft^3 (300 ft^3/359 ft^3 = .835 moles)

30 lbs x 1 mole/18 lbs = 1.665 moles + .835 moles = 2.5 moles

Because of the high temperatures, the relative humidity is zero.

Energy used for Water Removal (From CE Steam Tables, Reference #5)

(1201 BTU's - 38 BTU's)(30 lbs/min) = 34,890 BTU/min

34,890 BTU/min x 60 min/hr x 24 hr/day = 50.24×10^6 BTU/day

50.24×10^6 BTU/day x 200 days/year = 10×10^9 BTU/year

Energy Used for Make-up Air (From Conservation of Mass & Energy, Reference #14)

(6.96 BTU/mole^{o}F) or (.24 BTU/lb^{o}F)

.835 moles (6.96 BTU/mole^{o}F)($400^{o}F-70^{o}F$) = 1,918 BTU's/min

1,918 BTU's/min x 60 min/hr. x 24 hr/day = 2.762×10^6 BTU/day

2.762×10^6 BTU/day x 200 day/year = 5.52×10^8 BTU/year

BTU USE PER DAY = 53.00×10^6 BTU/day

BTU USE PER YEAR = 10.55×10^9 BTU/year

Natural Gas Used (345,168 BTU/mole or 359 ft^3)

For one day 53.00×10^6/345.168 BTU/mole = 153.5 moles

For one year 10.55×10^9/345,168 BTU/mole = 30,565 moles

30,565 moles x 359 ft^3/mole/1000 ft^3/mcf = 10,972 mcf

10,972 mcf x $4.10/mcf = $44,988/year

Energy Cost Comparisons

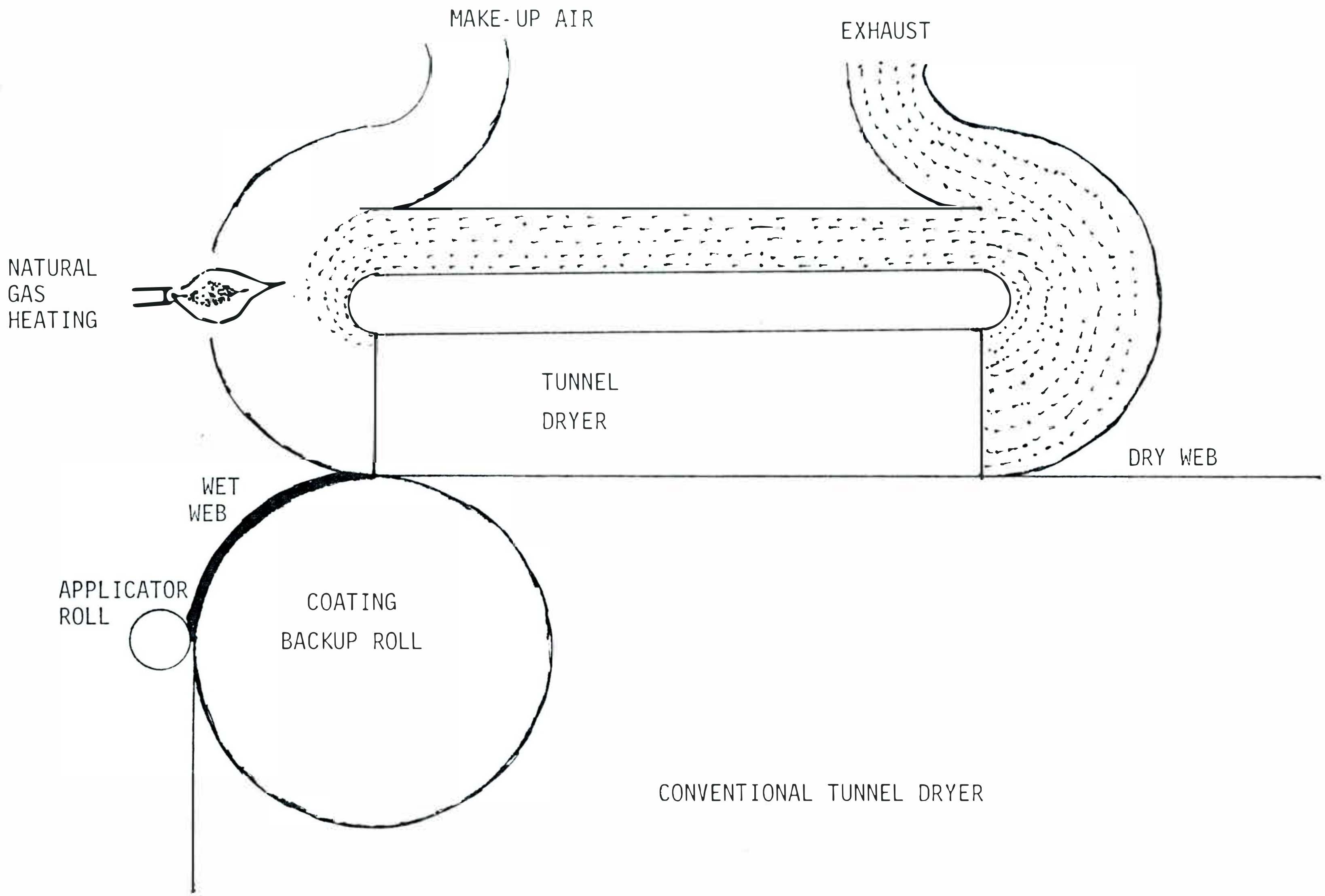
Heat Pump		Year		Gas System (300°F)
$11,700	. . . . . .	One	. . . . . .	$15,670
X 1.1				X 1.2
$12,870	. . . . . .	Two	. . . . . .	$18,800
X 1.1				X 1.2
$14,160	. . . . . .	Three	. . . . . .	$22,560
X 1.1				1.2
$15,575	. . . . . .	Four	. . . . . .	$27,070
X 1.1				X 1.2
$17,135	. . . . . .	Five	. . . . . .	$32,485
X 1.1				X 1.2
$18,850	. . . . . .	Six	. . . . . .	$38,980
X 1.1				X 1.2
$20,735	. . . . . .	Seven	. . . . . .	$46,775
X 1.1				X 1.2
$22,810	. . . . . .	Eight	. . . . . .	$56,130
X 1.1				X 1.2
$25,090	. . . . . .	Nine	. . . . . .	$67,355
X 1.1				X 1.2
$27,600	. . . . . .	Ten	. . . . . .	$80,825

Year	Difference in Cost
One	$ 3,970
Two	5,930
Three	8,400
Four	11,495
Five	15,350
Six	20,130
Seven	26,040
Eight	33,320
Nine	42,265
Ten	53,225

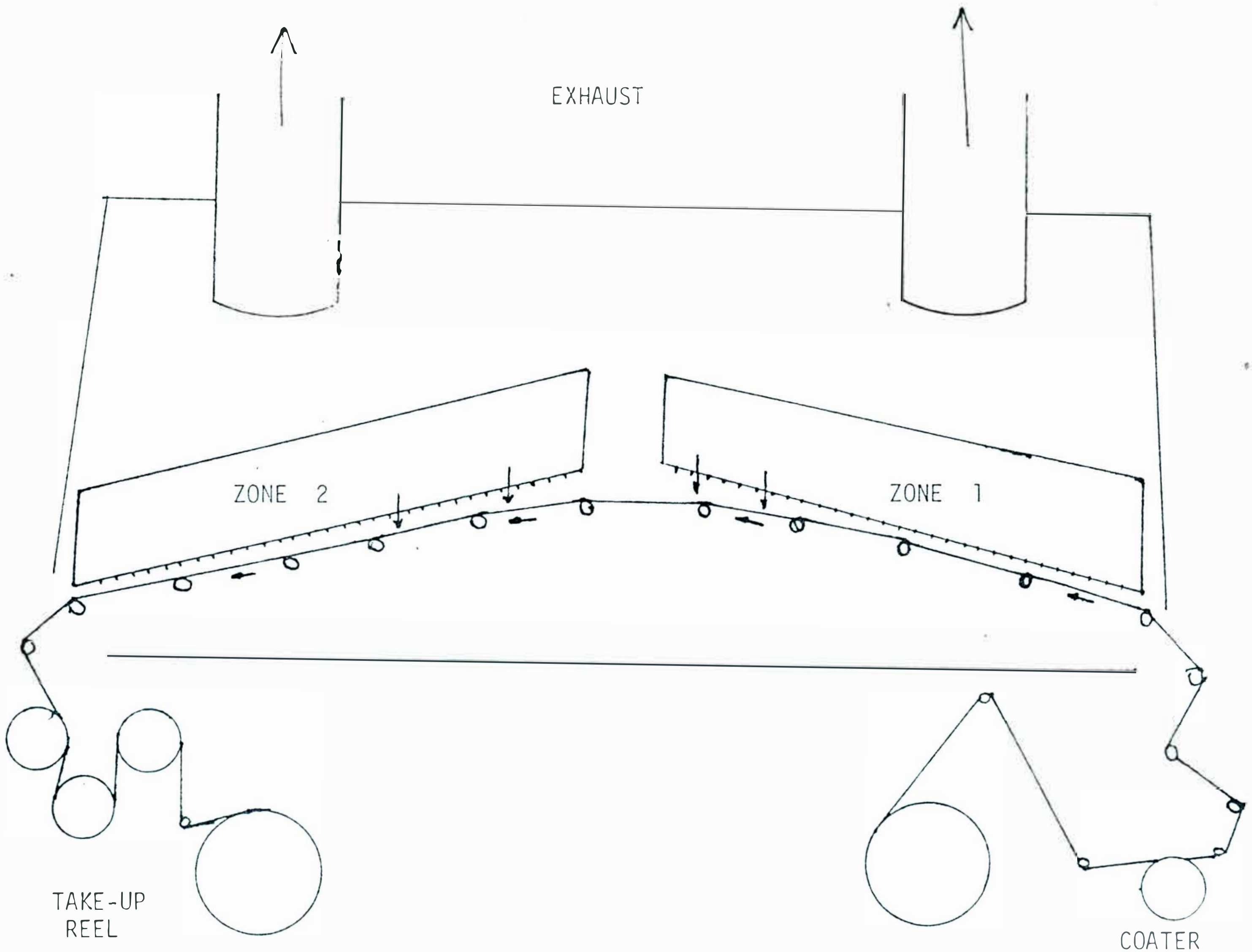
$220,125, Saved Over Ten Years.

Payback Achieved at 6.7 Years.

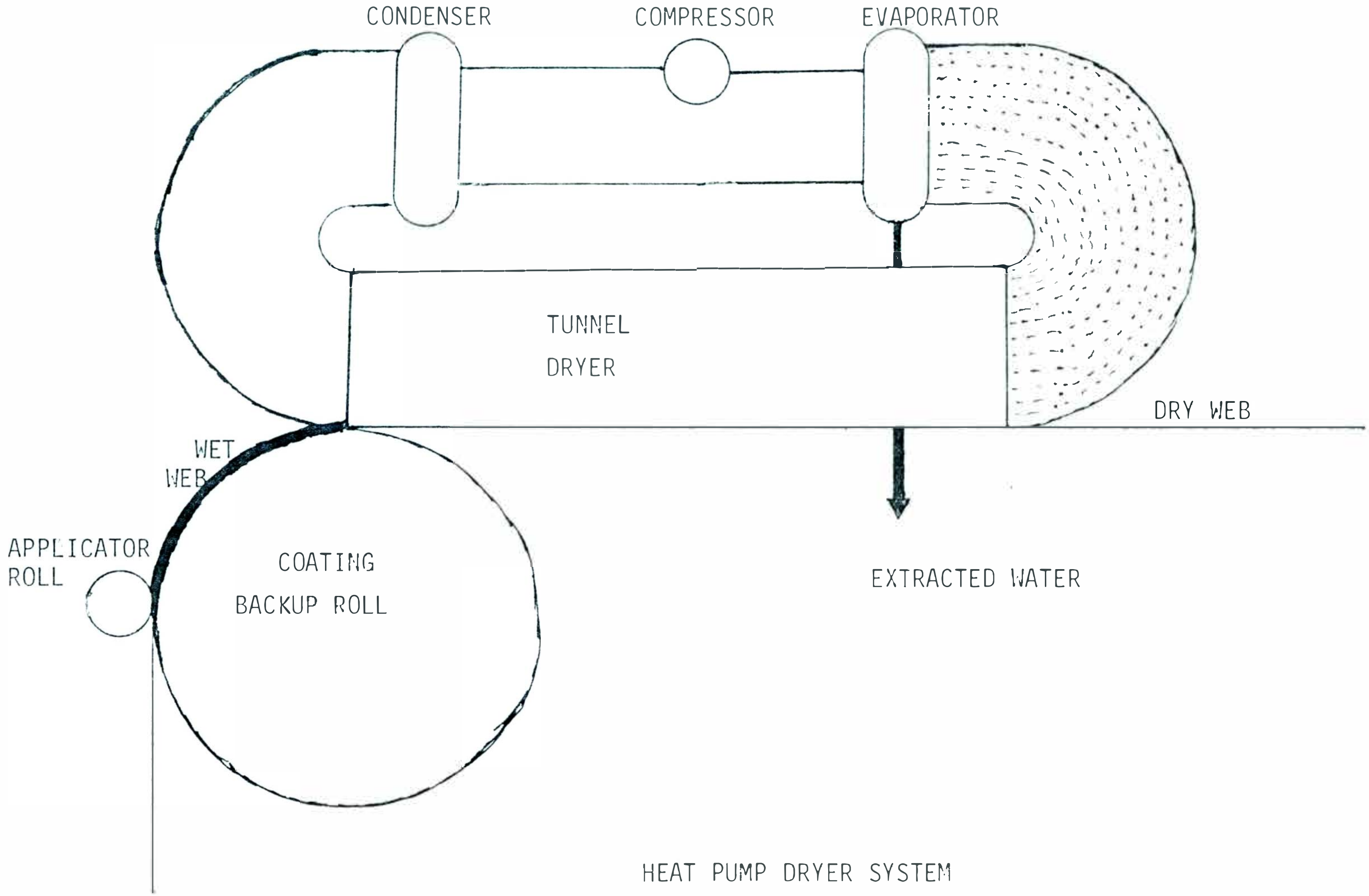
APPENDIX II



CONVENTIONAL TUNNEL DRYER



ARCH-TYPE DRYER (SOLVENT COATER)



HEAT PUMP DRYER SYSTEM

TERMS[3,10,13]

C.O.P.	The rate of performance at which a heat pump operates is called the Coefficient of Performance or C.O.P. The formula to find the C.O.P. is C.O.P. = $T_2/(T_2-T_1)$. The closer T_1 is to T_2 the higher the C.O.P. When the C.O.P. reaches one, the heat pump uses as much energy as it transfers.
EFF.	The ratio of evaporator and condensor temperatures is the Efficiency. EFF. = $(T_2-T_1)/T_2$ which says as an efficiency approaches one, the heat pump must work harder to produce the higher temperature.
T_1	The absolute temperature of the evaporator.
T_2	The absolute temperature of the condensor.
Compressor	The heart of the heat pump. By taking a gas and compressing it to a liquid it forces the working fluid (refrigerant) to give up its heat of vaporization.
Condenser	This is a part of the heat pump that will take the super heated liquid and pass it through a high pressure cooler. This will allow the liquid to give up the additional heat.

Tons of Refrigeration	One ton of refrigeration is the energy equivalent to melt one ton of ice in one day. This is the equivalent of 288,000 BTU's.
Throttle	The throttle is located between the condenser and the evaporator. It is shaped like a cone speeding up the flow and further compressing the refrigerant.
Expansion Valve	The expansion valve is located in place of the throttle and its function is to cause the liquid to expand and turn to a gas. In doing this the gas will absorb energy from the surroundings.
Evaporator	In this section of the heat pump the refrigerant which has given it's heat up in the condenser, expands into a gasous state, drawing the needed heat from the surroundings.
Refrigerant	Sometimes called the "working" fluid, the refrigerant carries the heat between the two mediums. Water has been used as a refrigerant, mostly in combination with ammonia. Other fluids/gasses include freon, ammonia, propane, ethane, in short, almost any organic gas with water and sulfur dioxide being the notable exceptions, can be used as a refrigerant.

Heat Sink — A medium used to remove waste thermal energy from a process.

Heat Source — A medium used to provide heat to a heat pump. Most commercial and residential systems rely on ambient air to provide necessary thermal energy. Many new systems as well as existing ones are looking into solar enhancement as a way of improving the source.