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AIR CONDITIONING WASTE HEAT TO DOMESTIC HOT WATER-A STUDENT DESIGN PROJECT

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ABSTRACT

The goal of the "Domestic Hot Water Heater Using Air Conditioner (A/C) Waste Heat" design project was to introduce students to designing mechanical systems in the "ETME475-Mechanical Systems Design" course. The design project was assigned to two Mechanical Engineering Technology students as their second design project in the course. Students were asked to do their own literature search and create their own designs. Both of them decided to use a concentric-tube heat exchanger to extract heat from hot refrigerant gas to heat water residing in domestic hot water heater tank. Their literature search led them to some manufacturers. Since delivery time for concentric-tube heat exchanger was too long, we purchased a side-by-side-tube heat exchanger and got it installed on our Heat Pump. Some test runs were conducted to measure the efficiency of the unit and its effect on the Coefficient of Performance (COP) of the Heat Pump when heat pump is operated in A/C mode. Contrary to our expectations, results indicate that, COP values have been reduced by about 22%. Measured efficiency of the unit was about 18%. Students have designed a concentric-tube heat exchanger, turned in their final reports and orally presented their designs to the class.

NOMENCLATURE

A = Total tube surface heat transfer area
ADC = Analog to Digital Converter
D = Pipe inside or equivalent diameter
LMTD = Log mean temperature difference
Nu = Nusselt number
Q = Heat transferred per unit time
Pr = Prandtl number
Re = Reynolds number
R_T = Total thermal resistance
T_{h1} = refrigerant inlet temperature
T_{h2} = refrigerant exit temperature
T_{c1} = Water exit temperature
T_{c2} = Water inlet temperature
U = Overall heat transfer coefficient
cfm = Cubic feet per minute
gpm = Gallons per minute
h_i = Water-side heat transfer coefficient
h_o = refrigerant-side heat transfer coefficient
k = Thermal conductivity
m = mass flow rate
Δx = Wall thickness

INTRODUCTION

To cool indoor air, air conditioners or heat pumps (HP) operated in A/C mode pump heat from indoors to outdoors. To improve efficiency of A/Cs, ground water may be used to cool condensers. Such systems are called geothermal A/C's or Heat Pumps and they are fairly expensive. Whether it is air or ground water cooled, heat removed from indoors is dumped to the environment and is wasted. Some or all of this heat may be used to obtain domestic hot water and at the same time the efficiency of the A/C process may be improved. Compressed refrigerant gas exiting from the compressor at high temperature and pressure (140-190 ^{o}F, 200-250 psi) enters into a cross-flow heat exchanger and transfer its heat to heat water. When there is enough water flow in the heat exchanger, refrigerant gas may be cooled down to within 10 degrees-F of entering water temperature. When entering water temperature is less than ambient air temperature, efficiency of A/C will be improved. At the same time, water is heated without any cost. It was expected, and proven by the measurements, that depending on the water flow rate in the heat exchanger, hot water temperatures up to 130 ^{o}F can obtained. When water temperature entering into heat exchanger reaches to ambient air temperature, there will not be any improvement on the efficiency of the A/C process.

Students in the Mechanical Engineering Technology program are required to take one Systems Design course during the last year of their program. Students are assigned to design a system or systems that require use of the knowledge that they have acquired in lower level courses. Sometimes, if the project is large enough, they are assigned a group project. "ETME 475-Mechanical Systems Design" course is a three credit-hour course, carrying 2 credit-hours for the lecture and one credit-hour (two contact-hours) for laboratory. As part of the requirement for this senior level course, the “Domestic Hot Water Heater Using A/C Waste Heat” design project was assigned to two Mechanical Engineering Technology students as their second design project. Students were asked to do their own literature search and create their own designs. After reviewing their designs, modifications were made to create the final designs. Since there was not enough time left to construct and test the heat exchanger, we purchased a side-by-side-tube cross flow heat exchanger and tested it using our Heat Pump.

Heat pumps, installed for space heating and cooling, operating in heating mode may also be used to obtain domestic hot water. Although it is more economical to heat water using heat pump, it will reduce heat pump’s heating capacity during the times when water needs to be heated. They do not recover wasted heat; rather they recover heat from outdoor air and use it to heat water.

Water heating heat pumps installed indoors and operated in heating mode may also be used to heat water during summer. Byproduct of such a system is cooling of indoor air. However, when there is no need to heat water, there will not be any cooling obtained.

WHAT IS A HEAT PUMP

Heat pumps (HP), when operated in heating mode, are reversed air conditioners (A/C). They pump heat from outdoors to indoors. Whereas air conditioners pump heat from indoor to outdoors. Whether it is an A/C or HP they both have an outdoor unit and an indoor coil. Outdoor unit has a compressor, an outdoor coil and a circulation fan. Compression raises gas temperature, thus heat can be removed by blowing air across the coil. Removing heat cools the refrigerant gas and it condenses and becomes liquid. Compressed liquid is expanded through a throttling valve into evaporator coil at low pressure. Suction side of the compressor creates low pressure. When liquid flashes into vapor inside the evaporator coil at low pressure, it gets very cold and cools the coil to low temperatures. When air is blown across the evaporator coil, air is cooled. Heat pump is a device that can reverse functions of condenser and evaporator coils using a reversing valve. Therefore, it can be used as a cooler during summer and as a heater during winter. In A/C mode, indoor coil is evaporator (cold surface) and outdoor coil is condenser (hot surface). Heat is transferred from indoor air to cold refrigerant gas in the evaporator coil and is carried to the condenser coil. From condenser coil, heat is transferred to outdoor air. In HP mode, a reversing valve reverses functions of the coils. Thus heat can be transferred from outdoors to indoors. A schematic of the system showing summer and winter operations are given Fig. 1 and Fig.2 [1]. In the figures, red color refer to warmer air and refrigerant, where as blue color refer to colder air and refrigerant.

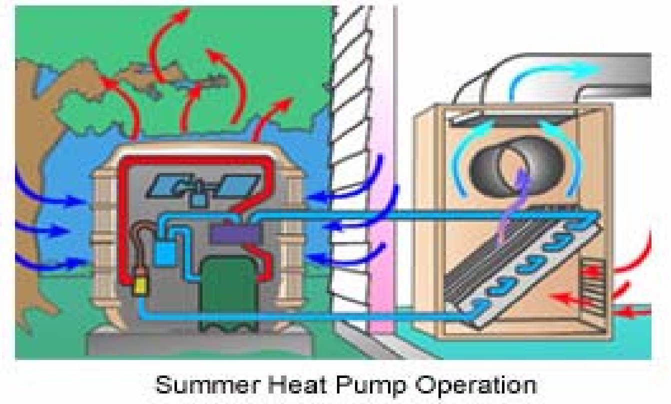

FIGURE 1. HEAT PUMP OPERATION IN COOLING MODE[1].

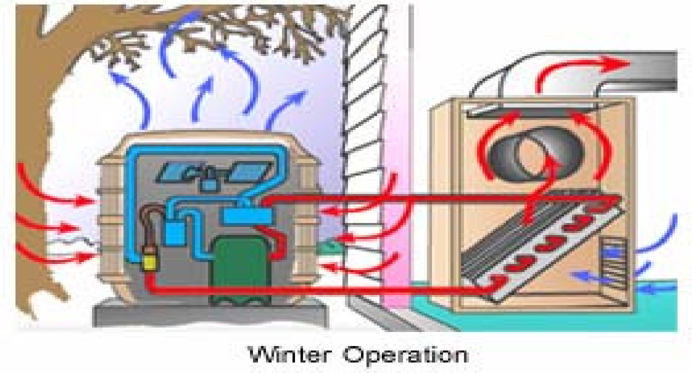

FIGURE 2. HEAT PUMP OPERATION IN HEATING MODE [1].

COMMERCIALLY AVAILABLE HEAT EXCHANGERS

During literature search students were able to locate several manufacturers [2-6]. Technical names for these units are: Desuperheater, Desuperheater Water Heater, Domestic Hot Water Heat Exchanger, Energy Recovery Unit, Energy Conservation Unit (ECU), Heat Recovery Unit, and Waste Heat Water Heater. Most of them are either concentric-tube or side-by-side-tube design. Commercial units are required to have refrigerant venting system to prevent refrigerant gas or liquid leaking into hot water. The purchased Heat Controller, Inc. [6] DS06 unit has side-by-side coiled tube design as shown in Fig. 3. There is no separate channel for refrigerant venting. Doucette Industries [3] AC series heat recovery units have concentric tube design with water-tube clean-out plugs. refrigerant venting is done through a clearance between the water tube and the refrigerant tube as shown in Fig.4.

Heat recovery units usually are placed outdoors, nearby the outdoor unit to minimize the length of refrigerant tubing as shown in Fig. 5. Most units come with freeze protection circuit or it is an option that can be added later.

FIGURE 3. HEAT CONTROLLER DS06, COILS EXPOSED.

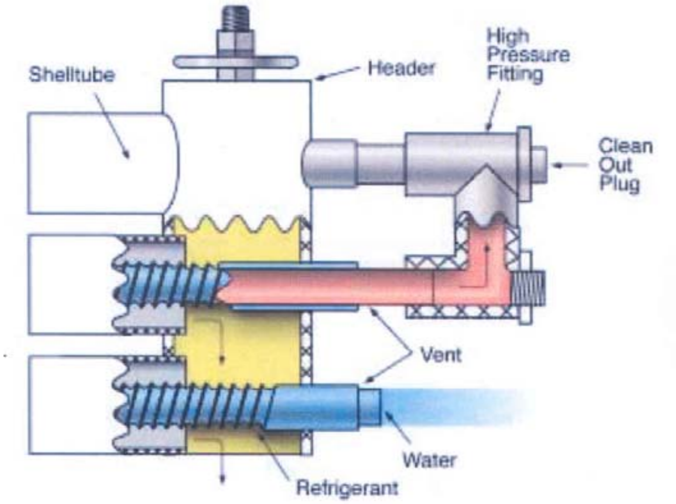

FIGURE 4. AC SERIES, CONCENTRIC-TUBE HEAT RECOVERY UNIT FROM DOUCETTE INDUSTRIES, INC. [3].

THE PURCHASED UNIT

As mentioned before, DS06 ECU was purchased form ACforSale, Inc. [7]. The purchased unit has a circulation pump, a mixing valve. Thermal switches are used to enable or disable the water circulation pump. Normally open switch turns the circulation pump on when refrigerant gas temperature reaches to 120 ^{o}F at the entrance to the ECU to prevent reverse heat transfer from hot water to refrigerant. Normally closed switch turns the circulation pump off when the water temperature at the entrance to the ECU reaches to 140 ^{o}F to limit water temperature increase to code requirements. Since there is no cold water connection to mix, the purpose of mixing valve, set at 120 ^{o}F, must be to reduce water flow rate through ECU so that water can be heated to about 120 ^{o}F. Unit is a side-by-side-tube, cross flow heat exchanger where exiting water receives heat from very hot refrigerant gas. As refrigerant cools down it can still transfer heat to cooler water entering into ECU. A typical connection to a hot water heater tank is shown in Fig. 6.

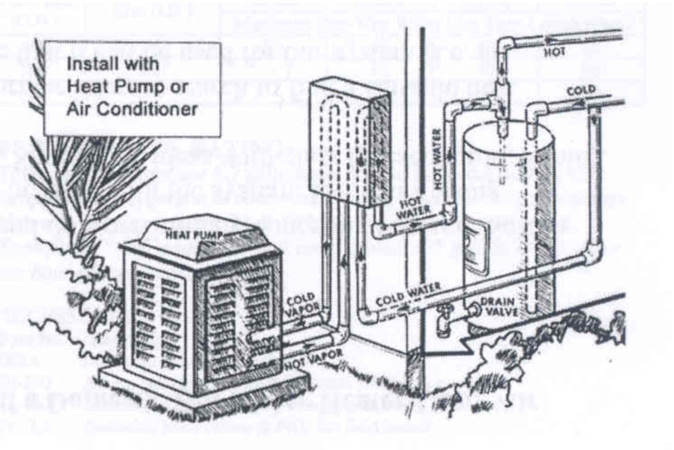

FIGURE 5. A TYPICAL INSTALLATION FOR HEAT RECOVERY UNITS [2].

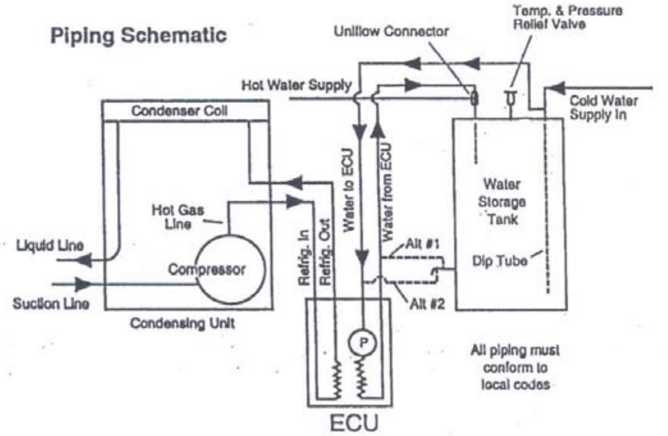

FIGURE 6. TYPICAL CONNECTIONS FOR DS06 TO A WATER HEATER [6].

STUDENT DESIGN PROJECT

This project was assigned to two students just to test the idea of heating water using A/C waste heat as well as teach them how to create a new product. Before I assigned this project, I had done some preliminary search for heat exchangers specifically designed for this purpose. Unfortunately, my search did not lead to any manufacturers. However as students and I continued on internet search, we came across some technical terms like desuperheaters, heat recovery units, etc. These terms led us to several manufacturers. Internet links to the documents related with the products were shared and some PDF files were e-mailed or printed and distributed to the students. Our students do not take a Heat Transfer course, therefore parts of chapter 10 (Heat Exchangers) of Holman's textbook [8] was covered in class. In addition, calculation of overall heat transfer coefficient (U-value), modes of heat transfer (conduction, convection and radiation), correlations for laminar and turbulent flow heat transfer coefficients were also covered. Although refrigerant R-22 is condensing in the heat exchanger, there was not enough time to get into condensation heat transfer and cover the condensation correlations.

After carefully reviewing the available designs, discussing advantages and disadvantages of concentric-tube and side-by-side-tube heat exchangers, students have agreed to design a concentric-tube heat exchanger with refrigerant bleed (vent). Adding a bleed tube meant additional barrier for heat flow. As seen in Fig. 4, it seems that in commercial desuperheaters a helical groove is cut on the outer surface of the water tube and this tube was inserted into another tube making it sure that both tubes touch one another to reduce conduction resistance. Even if two tubes are touching without any clearance, refrigerant can still escape through the helical groove. An outer tube is fitted over the vent tube to carry refrigerant. Students have used similar designs with some variations on creating refrigerant passages and packaging the unit.

Some example calculations were carried out to teach students how to calculate U-values. For simplicity, a plane wall was assumed. For a plane wall, total heat transferred is given by:

$$Q=U*A*(\Delta T)_{LMTD} \tag{1}$$

where

$$U=1/R_T \tag{2}$$

$$(\Delta T)_{LMTD}=\frac{(T_{h2}-T_{c2})-(T_{h1}-T_{c1})}{\ln[\frac{(T_{h2}-T_{c2})}{(T_{h1}-T_{c1})}]} \tag{3}$$

and

$$R_T=1/h_i+\Delta x/k+1/h_o \tag{4}$$

Calculation of U-value required calculation of refrigerant-side (h_o) and water-side (h_i) heat transfer coefficients as well as refrigerant bleed clearance thermal resistance, ($\Delta x/k$). This in turn required calculation of Reynolds numbers to estimate heat transfer coefficients using laminar and turbulent flow correlations [8]:

$$Nu=h*D/k=0.023*Re^{0.8}*Pr^{0.4} \tag{5}$$

for turbulent flow, and

$$Nu=4.0 \tag{6}$$

for laminar flow. "D" is diameter for the water tube and equivalent diameter for the refrigerant tube. Although it can be calculated or guessed that water flow is laminar, we had no idea what to use for the refrigerant velocity. Most likely flow is turbulent with refrigerant being cooled and condensed. Since condensation heat transfer coefficients are fairly high we can assume its film resistance may be neglected compared to water film resistance. Assuming that there is good contact between the refrigerant bleed and water tubes, refrigerant bleed clearance resistance can also be neglected. That leaves us with water film resistance with the end result of

$$U=h_i \tag{7}$$

For a 5/8 in (1.59 cm) O.D., 0.55 in (1.4 cm) I.D. water tube, using equations (6) and (7), one can calculate U ≈ 33 Btu/hr/ft^2/^{o}F.

Although this value is less than the minimum value of 50 given in Holman's [8] textbook, students were asked to use an average U-value of 100 Btu/hr/ft^2/^{o}F given for "refrigerant R-12 condenser with water coolant". Other used data are given in Table 1. R-12 and R-22 have similar properties.

TABLE 1. DATA FOR HEAT EXCHANGER CALCULATIONS.

Refrigerant inlet temperature, T_{h1}	140 ^{o}F
Refrigerant outlet temperature, T_{h2}	100 ^{o}F
Water inlet temperature, T_{c2}	60 ^{o}F
Water outlet temperature, T_{c1}	130 ^{o}F
Heat Pump capacity (in A/C)	2-tons
Heat pump COP (in A/C mode)	1.25
Wasted heat to be recovered, %	30 and 100

Enrolled students, Dan and Edward, were asked to design their heat exchangers to recover 30% and 100% of wasted heat respectively and use an estimated COP value of 1.25. Students did not submit final technical drawings of their designs. Dan's concentric, coiled tube design sketches are given in Fig. 7. Dan has used 1 3/8 in O.D. refrigerant tube, 7/8 in. O.D. refrigerant bleed tube and 0.5 in O.D. water tube. Coil diameter and

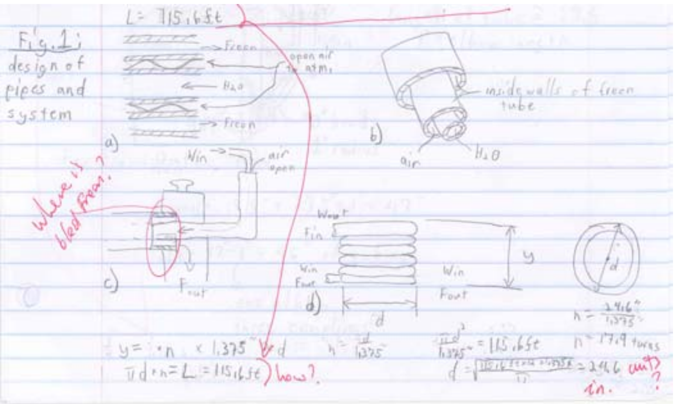

FIGURE 7. DAN's CONCENTRIC, COILED TUBE DESIGN.

height of the coil are the same at about 25 in. Coil has 18 turns and a total tube length of 115 ft.

EXPERIMENTAL SETUP AND INSTRUMENTATION

According to the installation instructions, students have selected the location of the ECU behind the heat pump at the right hand side just above the unit as shown in Fig. 8. Our technician have evacuated the refrigerant, brazed the unit and charged the system. Unit was spliced-in just before the reversing valve of the heat pump. Thus, ECU can be operated with heat pump both in A/C and in heating modes.

FIGURE 8. LOCATION OF ECU.

Experimental set up consisted of the ECU connected to Trane [9] XL1000, 2 ton, 10 SEER heat pump recently installed on our laboratory HVAC unit and associated instrumentation. Instrumentation consisted of seven Copper-Constantan thermocouples and a computer data acquisition system. Thermocouples were used to measure temperatures of refrigerant, water, air and ambient air. A computer data acquisition system was used to record temperatures. Indoor airflow rate was previously measured using Alnor LoFlo balometer [10, 11]. Thermocouple numbers, measured values, ADC channel number assignments and plotting colors are given in Table 2.

Data acquisition system consisted of a Pentium III, 450 MHz computer, a Data Translation [12] DT2805-5716, low level, 16-bit data acquisition board and ASYST [13] software. The board was connected to a DT707-T screw terminal box, which supported thermocouple inputs with a reference junction occupying analog input channel "0". A picture of the data acquisition system is given in Fig. 9. Screw terminal box is seen at the top of computer with thermocouple connections. Trane outdoor unit is seen at the left hand side of the computer cart. The HVAC training unit is behind and at the right hand side of the cart.

TABLE 2. ADC CHANNEL ASSIGNMENTS AND PLOTTING COLORS.

Identification	Measured Value	ADC Channel #	Plotting Color
T0	Junction box temperature	0	
T1	ECU Water inlet temperature	1	Dark Blue
T2	ECU Water outlet temperature	2	Green
T3	Ceiling air exit temperature	3	Light Blue
T4	ECU refrigerant gas inlet temperature	4	Red
T5	Inlet air temperature to indoor unit	5	Purple
T6	Outdoor air temperature at the inlet to outdoor coil	6	Brown
T7	ECU refrigerant gas exit temperature	7	White

FIGURE 9. DATA ACQUISITION SYSTEM CONNECTED TO NEWLY INSTALLED HEAT PUMP.

MEASUREMENTS AND RESULTS

Limited tests were carried out to measure performance of the ECU and its effect on the COP of the heat pump operated in A/C mode. The ECU was connected to a water faucet. Water flow rate was adjusted to obtain hot water temperature of about 120 ^{o}F. Water inlet temperature was steady at about 70 ^{o}F. Hot water was discharged into a large bucket using a polyethylene tube connected to the water exit port of the ECU. When steady state conditions have reached, hot water was collected into a small container for a period of three minutes. Water flow rate and temperature rise on water was calculated and used to calculate ECU's heating capacity and its efficiency. For an ECU, efficiency is defined as the ratio of heat extracted from the refrigerant divided by the total heat rejected. Total heat rejected was calculated using the COP (=Heat extracted from the indoor air/Electrical energy input) value calculated by the data acquisition program [11] as shown in Table 3. Temperatures and calculated COP values were displayed and stored in a file. Fig. 10 is a graph of typical recorded data on May 2, 2007. Test duration was 30 minutes. ECU water flow rate was established at sample number of about 30. This is recognized by gradual decrease in refrigerant (gas-out) outlet temperature. Fig. 11 is a graph of recorded data during which the ECU was turned ON and OFF to observe its effect on COP. Test duration was 30 minutes. Turn OFF period is recognized by elevated refrigerant outlet temperature.

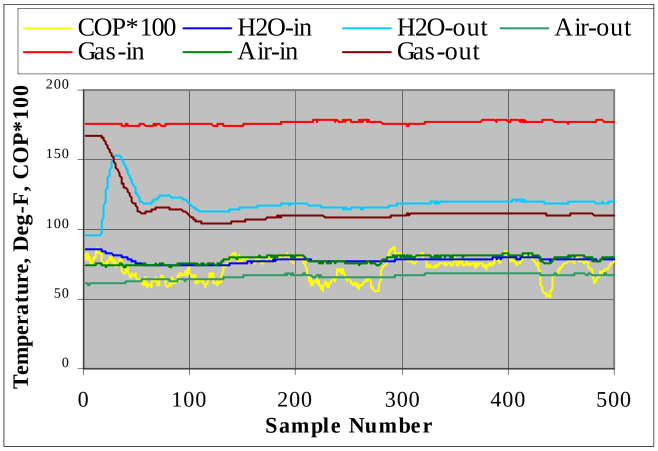

FIGURE 10. A GRAPH OF TYPICAL DATA RECORDED ON MAY 2, 2007.

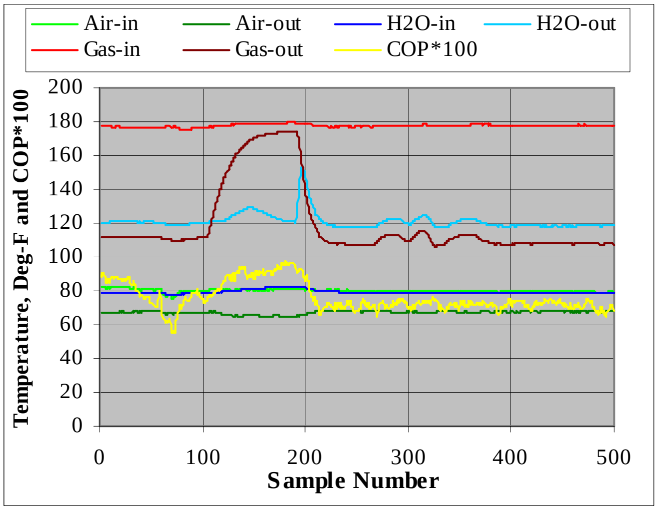

FIGURE 11. A GRAPH OF TYPICAL DATA RECORDED ON MAY 2 DURING WHICH ECU WAS TURNED ON AND OFF.

Summary of the key calculated values obtained from the data given in Fig. 10 and Fig 11 is given in Table 3.

TABLE 3. KEY CALCULATED VALUES OBTAINED FROM FIG. 10 AND FIG. 11 DATA.

From Fig. 10:

Sample # range used: 150-200 and 300-450

Average water-in temperature = 78.2 ^{o}F

Average water-out temperature = 118.4 ^{o}F

Average water flow rate = 1.26 lb/min

Average air-in temperature = 80.7 ^{o}F

Average air-out temperature = 67.7 ^{o}F

Indoor air flow rate = 520 ft^{3}/min

Average refrigerant-in temperature = 176.6 ^{o}F

Average refrigerant-out temperature = 109.8 ^{o}F

Average COP = 0.765

Q_{H2O} = m*Cp*(T2-T1) = 3039 Btu/hr

Q_{Air} = 1.08*cfm*(T5-T3) = 7300 Btu/hr

Q_{total} = Q_{Air} + Q_{Air} /COP = 16840 Btu/hr

ECU efficiency = Q_{H2O}/ Q_{total} = 18.0 %

From Fig 11:

Sample # range used: 150-180 and 375-500

Average COP when heater was OFF = 0.919

Average COP when heater was ON = 0.714

Reduction in COP = 22.3 %

DISCUSSION OF RESULTS

As seen in Table 3, calculations show that measured ECU efficiency is 18%. Since manufacturer has rated ECU's efficiency based on the cooling capacity of the air conditioner without specifying COP value, it is not possible to compare measured and given values. The manufacturer, Heat Controller, Inc., has stated "These units will produce 5-7gallons per hour of hot water, (40 ^{o}F temperature rise) per ton of compressor rating, based on 250 psi minimum high side pressure using R-22..". If we assume COP of their unit is same as our unit, rated efficiency of ECU will average to 23.8% (=2*500*gpm*(T2-T1)/16840), which is about 32% higher than our measured value of 18%. From Table 3, heat extracted from the air is only 7300 Btu/hr. This corresponds to 0.608 tons of cooling (=7300/12000) which is very low compared to its rated capacity of 2-tons (24 000 Btu/hr). One reason may be the low indoor air flow rate. Air flow rate through the evaporator coil is only 520 cfm instead of 800 cfm recommended value.

However smaller flow rate should have produced larger temperature difference than the measured value of 13 ^{o}F. Since refrigerant charge was correct, I wonder if our unit is defective. Nevertheless, whether the unit is defective or not, it should not change the efficiency of the ECU substantially.

To my surprise, calculations also show that COP of the A/C has decreased by about 22%. This large drop may be associated with the A/C not performing according to the manufacturer's specifications as well as due to the fact that cooler refrigerant leaving the condenser have reduced compressor head pressure effecting its performance. Condenser refrigerant (R-22) exit pressure and temperatures were about 230 psi and 95 ^{o}F with ECU OFF and about 200 psi and 91 ^{o}F with ECU ON.

CONCLUSIONS

As part of systems design course, students have designed a concentric-tube heat exchanger to recover wasted heat from an A/C. This was their second design project in class. They turned in their final reports and orally presented their designs to the class. Since there was not much time to construct the heat exchanger and we were able to locate some suppliers, we have purchased one and got it installed on our Heat Pump. Limited test runs indicate that side-by-side tube design ECU has an efficiency of about 18%. However it was surprising to see that it reduced A/C efficiency by 22%.

Students have enjoyed working on a project that has real world applications.

Follow-up research will measure efficiency of the ECU as a function of water inlet temperature and water flow rate. It is expected that higher water flow rate will improve water side heat transfer coefficient thus improve ECU's efficiency. Whereas higher water inlet temperature will reduce ECU's efficiency.

UNIT CONVERSIONS TABLE

1 Pa = 1.4504×10^{-4} psia
1 W = 3.41214 Btu/hr
1 W/(m^{2}.^{o}C) = 0.17612 Btu/(hr.ft^{2}.^{o}F)
1 kg/min = 2.2046 lb$_{m}$/min
1 m = 39.37 inches
1 m^{3} = 264.17 gal (US)
1 m^{3}/min = 35.315 cfm
^{o}C = 5/9*(^{o}F-32)

ACKNOWLEDGEMENTS

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