Experimental Investigations of Heat Pump for Domestic and Light Commercial Market.

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Abstract:

Heat pumps are very efficient heating and cooling systems and can significantly reduce your energy costs. The demand for air conditioning, water heating and potable water cooling, in domestic and light commercial markets is increasing rapidly. Concern for the environ¬ment and increasing price of energy forcing us to review conventional practices and develop novel alternatives. It is a challenge to develop new systems which use environment friendly refrigerants, while, ensuring low initial and operating costs.

This article presents heat pump for domestic and light commercial markets which Demonstrates several advantages. Performance of a 1 TR heat pump capable of catering to air conditioning, heating tap water and cooling potable water is indicated and shows that initial and operating cost can be reduced substantially and simultaneously.

Key words: Heat Pump, Air Conditioning System, Waste Heat Recovery, Heating Ventilating and Air Conditioning (HVAC)

Introduction:

Increasing use of energy and its effect on the environment is a matter of concern. Inefficient usage of energy can be controlled by using the latest techniques in design and manufacture of equipment. Proper application engineering is the key to reduce energy usage and associated fuel cost.

Cost reduction has become essential in order to survive in the global market. One way to achieve significant energy cost reduction, in HVAC & R applications, is by recovering and recycling waste heat. Co-generating cold and hot utilities can reduce energy consumption and a heat pump is one such device which can be used to deliver cold and hot utility simultaneously.

Heat Pump:

Heat Pump is a device mainly used for recovering the waste heat. The major application areas of this system are in Petroleum Refining and Petrochemicals, Chemical Industries, Wood Products, Food and Beverages, Nuclear power and other miscellaneous industries.

A heat pump is a device which pumps heat from a low temperature source to a high temperature sink, with the help of an external source of energy. Improving living standard and globalization is throwing up new challenges in coping with the increased demand for electricity. The demand for air conditioning, water heating and potable water cooling, in domestic and light commercial markets is increasing rapidly. Concern for the environment and increasing price of energy forcing us to review conventional practices and develop novel alternatives. It is a challenge to develop new systems which use environment friendly refrigerants, while, ensuring low initial and operating costs.

A Vapor Compression Heat Pump (VCHP) cycle is the same as that of the refrigeration cycle. The Heat Pump can be used to simultaneously cater to Air Conditioning (AC) requirement, along with Water Heating (WH) and Water Cooling (WC) needs. Tap water can be heated to 45°C. This hot utility can be used for bathing, cooking, dish washing, drying, laundry, etc. Potable water can be cooled to 20°C and be used for drinking. This Paper presents the Heat Pump, which can simultaneously cater to Air Conditioning, Water Heating and Water Cooling needs in domestic and light commercial applications in the range of 1 to 2 TR range.

Objectives:

1) Generate Cold and Hot Utilities Simultaneously using Heat pump.
2) Use of Heat Pump as Air conditioner, Water heater and Water Cooler.
3) To calculate the COP of Heat Pump at different modes (Air Conditioning, Air Conditioning +Water Heating, Air Conditioning +Water Cooling, Air Conditioning + Water Heating + Water Cooling)
4) To compare the COP of Heat Pump at different Modes.
5) To find Economics of Heat Pump Used for Commercial Application.

Experimental Work:

Background:-

Heating, ventilation and air conditioning (HVAC) systems account for 40% to 60% of the energy used in U.S. commercial and residential buildings. Proven technologies and design concepts, along with energy efficient HVAC technologies will allow these services to be provided with significant energy savings and lower lifecycle costs.

HVAC systems also have a significant effect on the health, comfort, and productivity of occupants. Issues including user discomfort, improper ventilation, and poor indoor air quality are linked to HVAC system design and operation and can be corrected by improved mechanical and ventilation systems. As with lighting systems, the productivity gains from a well designed and implemented HVAC system can result in savings that are many times the energy savings alone.

Experimental Setup

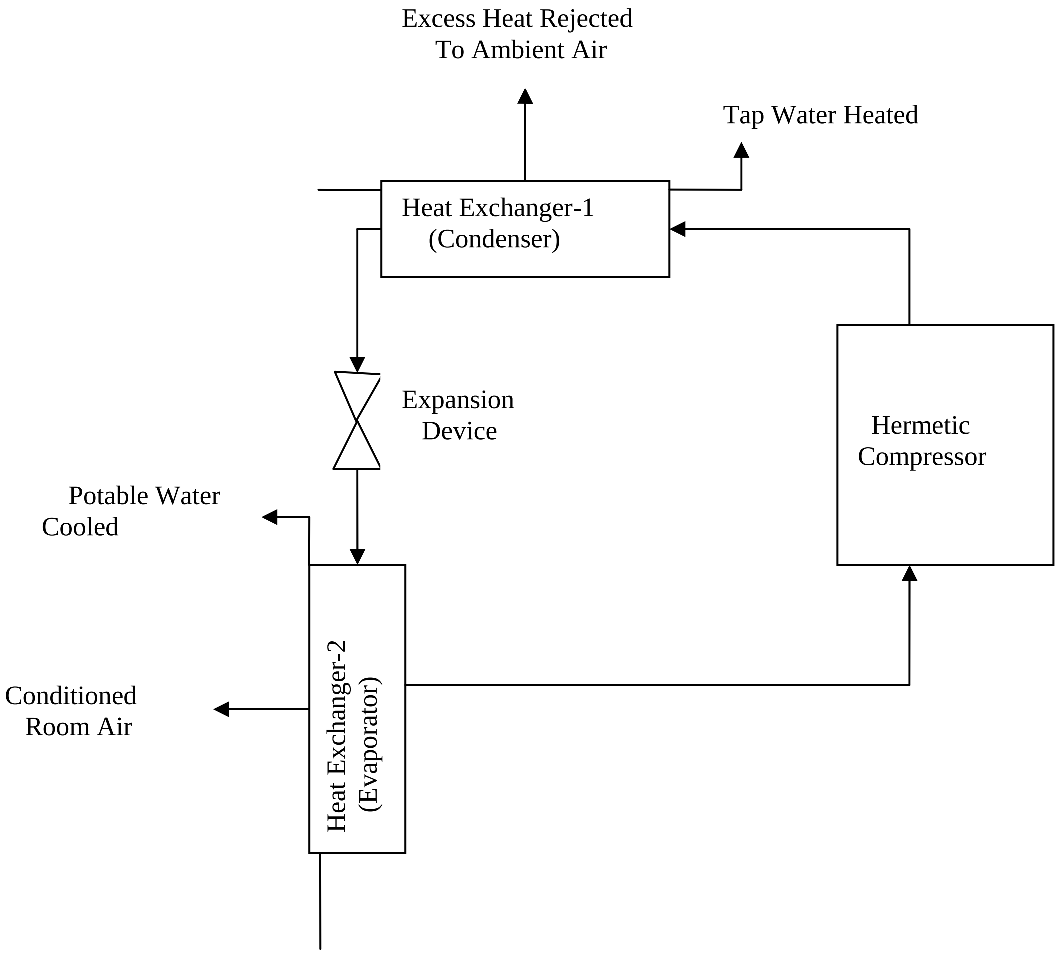


Figure No. 1

HOW DOES A AIR CONDITIONER WORK ?

A window air conditioner unit implements a complete air conditioner in a small space. The units are made small enough to fit into a standard window frame. You close the window down on the unit, plug it in and turn it on to get cool air. If you take the cover off of an unplugged window unit, you'll find that it contains:

- A compressor
- An expansion valve
- A hot coil (on the outside)
- A chilled coil (on the inside)
- Two fans
- A control unit

The fans blow air over the coils to improve their ability to dissipate heat (to the outside air) and cold (to the room being cooled). The cold side, consisting of the expansion valve and the cold coil, is generally placed into a furnace or some other air handler. The air handler blows air through the coil and routes the air throughout the building using a series of ducts. The hot side, known as the condensing unit, lives outside the building.

The unit consists of a long, spiral coil shaped like a cylinder. Inside the coil is a fan, to blow air through the coil, along with a weather-resistant compressor and some control logic. In larger buildings and particularly in multi-story buildings, the split-system approach begins to run into problems. Either running the pipe between the condenser and the air handler exceeds distance limitations (runs that are too long start to cause lubrication difficulties in the compressor), or the amount of duct work and the length of ducts becomes unmanageable. At this point, it's time to think about a chilled-water system.

HOW DOES A HEAT PUMP WATER HEATER WORK ?

1. Liquid (refrigerant) boils at a low temperature in an evaporator. Output is low temperature and low pressure vapor.
2. Pressure and temperature of vapor increased in the compressor. Output is high temperature and pressure vapor.
3. This high temperature gas then passes through the Heat exchanger-1. (Condenser) which provides excellent heat transfer characteristics. Heat Exchanger-1(Condenser), where it gives off its heat and returns to a liquid state. In this way we can get heated tap water to about 45°C
4. Liquid is returned to the evaporator after passing through a partially open valve (TX valve or capillary tube). Output is low pressure cold liquid ready to be evaporated again.

HOW DOES A HEAT PUMP WATER COOLER WORK?

1. Pressure and temperature of vapor increased in the compressor. Output is high temperature and pressure vapor. On refrigerant side output is warm liquid refrigerant.
2. Liquid is returned to the evaporator after passing through a partially open valve (TX valve or capillary tube). Output is low pressure cold liquid ready to be evaporated again.
3. A fan blows air across the heat exchanger-3 (Evaporator) which contains low temperature refrigerant. The refrigerant changes state from a liquid to gas as it passes through the heat exchanger-3 (Evaporator) absorbing heat from the air as well as from water circulating Heat exchanger-4 near by it. In this way we can get cooling potable water to about 20°C

Observations

1 TR Heat Pump was carefully tested at the laboratory. The water side temperatures were measured using RTD sensors Flow rate was measured manually by collecting water for 2 minutes in a container and weighing it. Single phase two wire electronic Wattmeter was used to measure the power input to the Heat Pump. Anemometer was used to measure the velocity of air.

Table: I
Observations at Air Conditioning Mode:

Sr. No.	Particulars	Readings
01	Velocity of Air in m/sec	3
02	Condenser pressure in lb/inch^2	210
03	Evaporator pressure in lb/inch^2	50
04	Condenser inlet Temperature in ^{0} C	51
05	Condenser outlet Temperature in ^{0} C	43
06	Evaporator inlet Temperature in ^{0} C	-4
07	Evaporator outlet Temperature in ^{0} C	24
08	Air inlet Temperature in ^{0} C	34
09	Air outlet Temperature in ^{0} C	18.5
10	Time taken for10 revolutions of energy meter in seconds	32

Table: II
Observations at Air Conditioning + Water Cooling Mode:

Sr. No.	Particulars	Readings					
01	Mass Flow rate of water in lit/min	3	2.7	0.9	0.7	0.5	0.4
02	Condenser pressure in lb/inch^2	210	210	210	211	211	211
03	Evaporator pressure in lb/inch^2	54	54	53	53	53	53
04	Condenser inlet Temperature in ^{0} C	50	50	50	50	51	51
05	Condenser outlet Temperature in ^{0} C	42	42	42	41.5	41	41
06	Evaporator inlet Temperature in ^{0} C	-4	-4	-4	-4	-4	-4
07	Evaporator outlet Temperature in ^{0} C	26	26	26	25	25	25
08	Air inlet Temperature in ^{0} C	34	34	34	34	34	34
09	Air outlet Temperature in ^{0} C	21	20	21	20	20	20
10	Water inlet Temperature in ^{0} C	27	27	27	27	27	27
11	Cold Water outlet Temperature in ^{0} C	27	27	25	25.5	24	23
12	Time taken for10 revolutions of energy meter in seconds	36	36	36	36	36	36
13	Velocity of Air in m/sec	3	3	3	3	3	3

Table: III
Observations at Air Conditioning + Water Heating Mode:

Sr. No.	Particulars	Readings					
01	Mass Flow rate of water in lit/min	3	2.7	0.9	0.7	0.5	0.4
02	Condenser pressure in lb/inch^2	209	209	209	209	201	210
03	Evaporator pressure in lb/inch^2	52	52	51	50	50	50
04	Condenser inlet Temperature in ^{0} C	50	50	50	50	51	51
05	Condenser outlet Temperature in ^{0} C	39	39	39.5	38	37.5	37
06	Evaporator inlet Temperature in ^{0} C	-5	-5	-5	-5	-5	-5
07	Evaporator outlet Temperature in ^{0} C	28	28	28	27	27	27
08	Air inlet Temperature in ^{0} C	34	34	34	34	34	34
09	Air outlet Temperature in ^{0} C	22	22	22	21	21	21
10	Water inlet Temperature in ^{0} C	27	27	27	27	27	27
11	Hot Water outlet Temperature in ^{0} C	35	36	40	42	43	45
12	Time taken for10 revolutions of energy meter in seconds	42	42	42	42	42	42
13	Velocity of Air in m/sec	3	3	3	3	3	3

Table: IV
Observations at Air Conditioning + Water Cooling + Water Heating Mode:

Sr. No.	Particulars	Readings					
01	Mass Flow rate of water in lit/min	3	2.7	0.9	0.7	0.5	0.4
02	Condenser pressure in lb/inch^2	210	210	210	211	211	211
03	Evaporator pressure in lb/inch^2	52	52	51	50	50	50
04	Condenser inlet Temperature in ^{0} C	50	50	50	50	51	51
05	Condenser outlet Temperature in ^{0} C	40	39.5	39	38.5	38	37.5
06	Evaporator inlet Temperature in ^{0} C	-5	-5	-5	-5	-5	-5
07	Evaporator outlet Temperature in ^{0} C	28	28	28	27	27	27
08	Air inlet Temperature in ^{0} C	34	34	34	34	34	34
09	Air outlet Temperature in ^{0} C	22	22	22	21	21	21
10	Water inlet Temperature in ^{0} C	27	27	27	27	27	27
11	Cold Water outlet Temperature in ^{0} C	27	27	25.5	25	24	23.5
12	Hot Water outlet Temperature in ^{0} C	35	36	39	43	43	44
13	Time taken for10 revolutions of energy meter in seconds	41	41	41	41	41	41
14	Velocity of Air in m/sec	3	3	3	3	3	3

Calculations

Coefficient of Performance (COP) Calculations

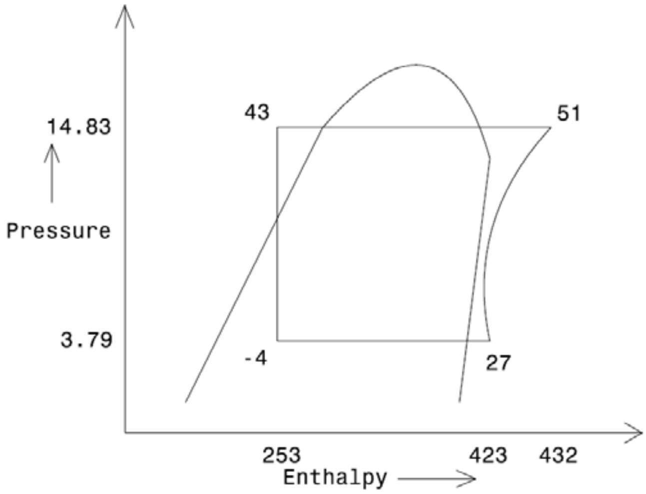
i) Theoretical COP:-

1) Air Conditioning Mode:

$$COP_{The.} = \frac{heo - hei}{hci - hco}$$

where,

heo= Enthalpy at evaporator outlet in kJ/kg,
hei= Enthalpy at evaporator inlet in kJ/kg,
hco= Enthalpy at condenser outlet in kJ/kg,
hci= Enthalpy at condenser inlet in kJ/kg,

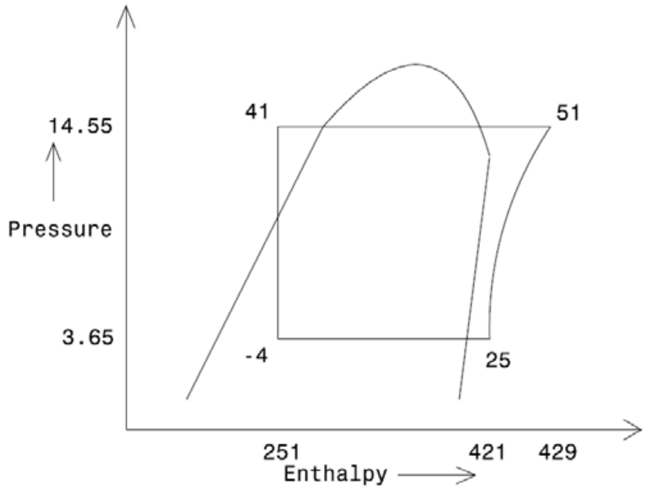


$$\therefore \; COP_{The.} = \frac{423 - 253}{432 - 253}$$

$= 0.949$

2) Air Conditioning + Water Cooling Mode:

$$COP_{The.} = \frac{heo - hei}{hci - hco}$$

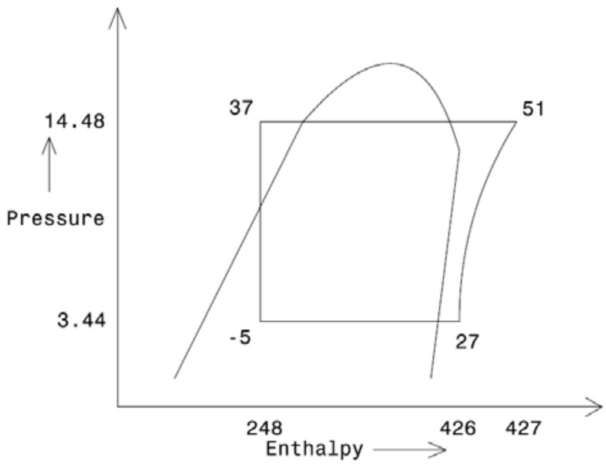


$$\therefore \; COP_{The.} = \frac{421 - 251}{429 - 251}$$

$= 0.955$

3) Air Conditioning + Water Heating Mode:

$$COP_{The.} = \frac{heo - hei}{hci - hco}$$

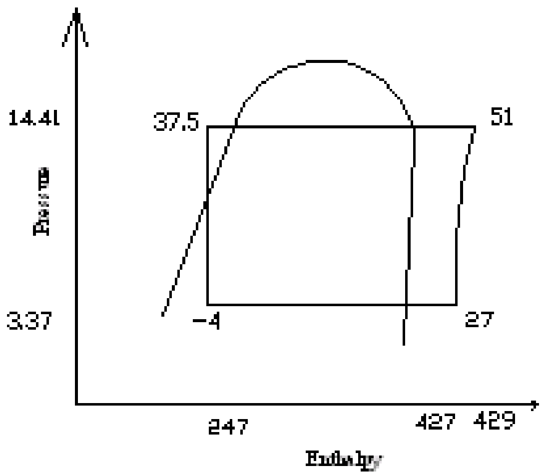


$$\therefore \quad COP_{The.} = \frac{426-248}{427-248}$$

$= 0.994$

4) Air Conditioning + Water Heating + Water Cooling Mode:

$$COP_{The.} = \frac{heo-hei}{hci-hco}$$



$$COP_{The.} = \frac{427-247}{429-247}$$

$= 0.989$

ii) Actual COP:-

Velocity of Air: 3 m/sec

∴Volume Flow rate = Area of duct x Velocity

= (0.3 x 0.26) x 3

= 0.26 m^3/sec

Mass flow rate of Air = Volume Flow rate of Air x Density of Air

…………………. Density of Air is 1.168 kg/m^3 at 27^0 C

= 0.26 x 1.168

= 0.30 kg/sec

1) Air Conditioning Mode:

$$COP_{act.} = \frac{Nact.}{Wact.}$$

&

$N_{act.}$= m x cp x ΔT

Where,

m= mass flow rate of air in kg/sec

cp= specific heat of air

ΔT= Temperature difference

∴ $N_{act.} = m \times cp \times \Delta T$

$= 0.30 \times 1.05 \times (34-18.5)$

$= 4.882$ k Watts.

Now,

$$W_{act.} = \frac{Nc \times 3600}{tc \times EMC}$$

Where,

Nc= No. of revolutions of Energy meter

tc= time required for 10 revolutions of energy meter

EMC = Energy meter constant

$$\therefore W_{act.} = \frac{10 \times 3600}{32 \times 600}$$

$= 1.875$ k Watts.

$$\therefore COP_{act.} = \frac{Nact.}{Wact.}$$

$$= \frac{4.882}{1.875}$$

$COP_{act} = 2.60$

2) Air Conditioning + Water Cooling Mode:

$$COP_{act.} = \frac{Nact.}{Wact.}$$

$N_{act.} = m \times cp \times \Delta T$

∴ $N_{act.} = m \times cp \times \Delta T$

$= 0.30 \times 1.05 \times (34-20)$

$= 4.41$ k Watts.

Now,

$$W_{act.} = \frac{Nc \times 3600}{tc \times EMC}$$

$$\therefore W_{act.} = \frac{10 \times 3600}{36 \times 600}$$

$= 1.66$ k Watts.

$$\therefore COP_{act.} = \frac{Nact.}{Wact.}$$

$$= \frac{4.41}{1.66}$$

$COP_{act} = 2.65$

3) Air Conditioning + Water Heating Mode:

$$COP_{act.} = \frac{Nact.}{Wact.}$$

&

$N_{act.} = m \times cp \times \Delta T$

∴ $N_{act.} = m \times cp \times \Delta T$

$= 0.30 \times 1.05 \times (34-21)$

$= 4.095$ k Watts.

Now,

$$W_{act.} = \frac{Nc \times 3600}{tc \times EMC}$$

$$\therefore W_{act.} = \frac{10 \times 3600}{42 \times 600}$$

$= 1.428$ k Watts.

$$\therefore COP_{act.} = \frac{Nact.}{Wact.}$$

$$= \frac{4.095}{1.428}$$

$COP_{act} = 2.86$

4) Air Conditioning + Water Cooling + water Heating Mode:

$COP_{act.} = \frac{N_{act.}}{W_{act.}}$

&

$N_{act.} = m \times cp \times \Delta T$

$\therefore N_{act.} = m \times cp \times \Delta T$

$= 0.30 \times 1.05 \times (34-21)$

$= 4.095$ k Watts.

Now,

$W_{act.} = \frac{N_o \times 3600}{t_0 \times EMC}$

$\therefore W_{act.} = \frac{10 \times 3600}{41 \times 600}$

$= 1.463$ k Watts.

$\therefore COP_{act.} = \frac{N_{act.}}{W_{act.}}$

$= \frac{4.095}{1.463}$

$COP_{act} = 2.79$

A) Heat Rejected by Air:-

Let

Air mass flow rate = Q = ρ x A x V

Where,

ρ = Density of Air in kg/m^3

A = Area of duct in m^2

$\therefore$ Q = 1.05 x (0.3 x 0.35) x 3

= 0.33 kg/ sec

Heat Rejected by Air:

= Q ($h_2 - h_1$)

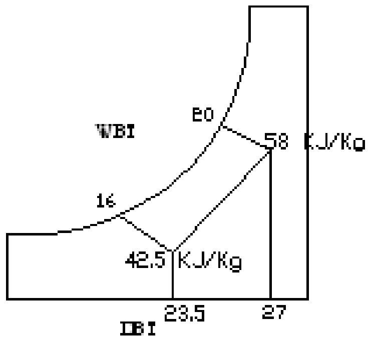
= 0.33 x (423-253)

= 56.1 k Watts.

Heat Rejected by Water in Evaporator:

Outlet	DBT	23.5^0 C	Inlet	DBT	27^0 C
	WBT	$16\ ^0$C		WBT	$20\ ^0$C

From Psychrometric Chart



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Specific Humidity (ω_1) = 0.0072 kJ/kg

(ω_2) = 0.012 kJ/kg

Relative Humidity (RH_1) = 38 %

(RH_2) = 52 %

Specific Enthalpy (H_1) = 42.5 kJ/kg

(H_2) = 58 kJ/kg

∴ Heat Rejected by Water

$q_p = Q (H_2 - H_1)$

where, Q = mass flow rate of water in kg/hr

= m

= 0.4 kg/min

= 0.4 x 60

= 24 kg/sec

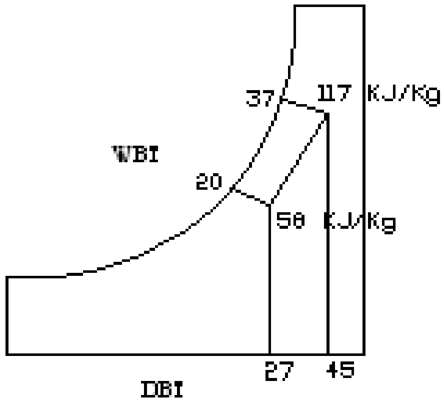
∴ q_p = 24 (58 - 42.5)

q_p = 372 k Watts.

Heat Absorbed by Water in Condenser:

Inlet	DBT	27^0 C	Outlet	DBT	45^0 C
	WBT	20^0 C		WBT	37^0 C

From Psychrometric Chart



We gat

Specific Humidity (ω_1) = 0.012 kJ/kg

(ω_2) = 0.030 kJ/kg

Relative Humidity (RH_1) = 52 %

(RH_2) = 65 %

Specific Enthalpy (H_1) = 58 kJ/kg

(H_2) = 117 kJ/kg

∴ Heat Rejected by Water

$q_p = Q (H_2 - H_1)$

where, Q = mass flow rate of water in kg/hr

= m

= 0.4 kg/min

= 0.4 x 60

= 24 kg/sec

∴ q_p = 24 (117 - 58)

q_p = 1416 k Watts.

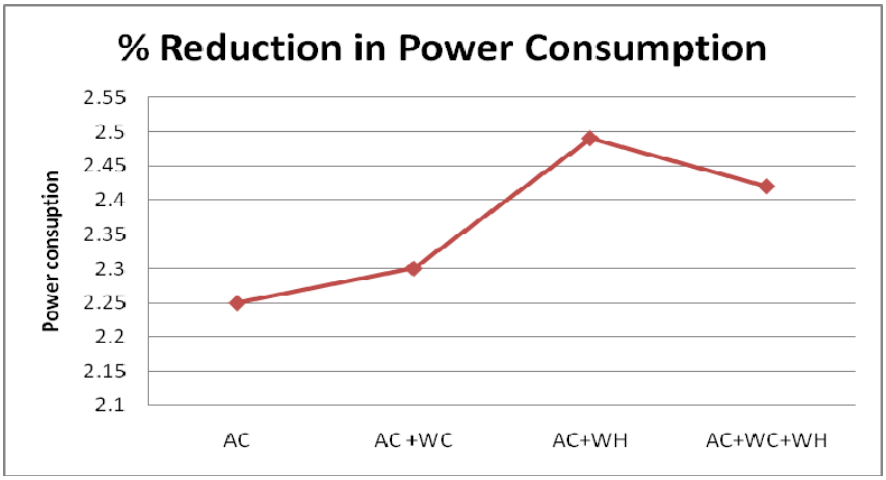
Results

Power Consumption

Sr. No.	Mode	Power Consumption In Watts
01	Air Conditioning	1.875 W
02	Air Conditioning + Water Cooling	1.66 W
03	Air Conditioning + Water Heating	1.428 W
04	Air Conditioning + Water Heating + Water Cooling	1.463 W

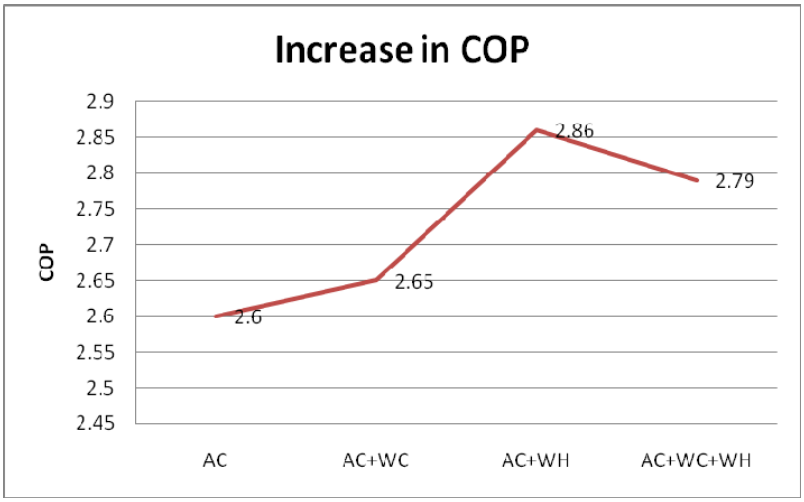
% Reduction in Power Consumption

Sr. No.	Mode	% Reduction
01	Air Conditioning + Water Cooling	11.22 %
02	Air Conditioning + Water Heating	24.06 %
03	Air Conditioning + Water Heating + Water Cooling	21.97 %



Increase in COP

Sr. No.	Mode	COP	% Increase
01	Air Conditioning	2.60	--
02	Air Conditioning + Water Cooling	2.65	2.22 %
03	Air Conditioning + Water Heating	2.86	10.66 %
04	Air Conditioning + Water Heating + Water Cooling	2.79	7.55 %



Economical analysis of Heat pump

Economics of using a 1 TR Window HP for a commercial application, of simultaneously conditioning air and heating water, is presented in Table below. Costs and benefits are compared with the conventional system consisting of a Split AC or Window AC for air conditioning and Electric Water Heater (EWH) for water heating. Initial costs of Split AC and Window AC are Rs 36,000/- and Rs 25,000/- respectively and are based on the cost of the conventional ACs in the market. Initial costs of Split HP and Window HP are estimated to be Rs 44,000/- and Rs 33,000/- respectively. Initial costs do not include taxes and duties. Cost of Electric Water Heater is taken as Rs 2,700/- for a 3 kW heater.

The analysis is based on the assumption that
1 TR air conditioning is required for 6 h/day for 280 days/yr,
Total hr/yr = 1680, and
The 3 kW water heater is required for 2 h/day for 365 days/yr,
Total hr/yr = 730, and

Type of System **Mode of Operation**		**Heat Pump** **AC + WH + WC**	**Window AC**	**Electric Water Heater**	**Water Cooler**
Initial Cost of the AC/HP	Rs	33000	25000		
Initial Cost of the Electric Water Heater (EHW)	Rs			2700	
Initial Cost of the (AC + EWH)/HP	Rs	33000	27700	33000	23500
EWH Capacity	kW			3.00	
HP Heating Capacity	kW	2.50		3.00	
Hours of Operation of EWH	h/yr			730	
Hours of Operation of HP in AC + WH Mode	h/yr	1680	1680		1000
Power Consumption of the AC/HP	Watt	1.70	2.18	2.00	4.5
COP of the AC/HP		2.79	2.60		
Cost of Electricity @ Rs 3 per Watt	Rs/yr	8568.00	10987.20	4380.00	13500.00
Saving in Cost of Electricity	Rs/yr	2418.20			
Total Saving (Cooling + Heating)	**Rs/yr**	**15460.80**			
Extra Investment for Heat Pump	**Rs**	**8000.00**			
Expected Payback	**months**	**6.2**			

Due to higher cooling COP and cooling capacity of the Heat Pump as compared to that of the Split AC and Window AC respectively, the total power consumed for cooling by the Heat Pump is less than that for the Split AC and Window AC respectively. This leads to energy cost savings of Rs 2418.20/yr using Heat Pump as compared to Split AC. Thus, the total saving in electricity cost is Rs 15460.80/yr..

Expected payback period for the Heat Pump works out to be 6.2 months. Indeed very attractive!

The above payback periods are calculated without accounting for the benefit of availing 100% depreciation in the very first year towards the cost of the HPs. This when accounted for will lower the effective cost of the Heat Pump, by another 35% for a profit making organization. In such situations the cost of the Heat Pumps will actually work out to be lower than that of conventional Window AC/ Split AC + Electric Water Heater option. Thus, the user can benefit from both, lower initial cost and lower operating cost.

Economic analysis for a domestic application, where the unit cost is about Rs 3/kWh as compared to Rs 6/kWh, will offer payback periods in the range of 12.2 to 12.4 months.

Industrial applications will be more attractive because of larger demand for hot utility, which will further increase the saving in energy used to produce the hot utility. Since, hot utility in industry may be generated using fuels instead of electricity the savings in fuel cost may be only slightly higher than the saving in electricity cost in the case of commercial applications.

Thus, these Heat Pumps can be used for reducing initial and operating cost not only in domestic and commercial markets, but also for industrial applications when properly engineered.

Features and Advantages of the Heat Pumps

Some features and advantages of the novel heat pump over the conventional air conditioners are listed hereunder:

1. Co-generation of air conditioning, cold and/or hot water simultaneously using a single unit – offers better COP compared to WAC/SAC when hot and/or cold water is tapped.
2. Instant–on–demand supply of hot and cold water – no storage required, no auxiliary pumps and controls required, hence lower initial and operating costs

3. Cooling capacity increases by 3.9 to 12.2% when hot and/or cold water is drawn.
4. Power required for air conditioning is reduced – 11.22 to 21.97 % decrease in power consumption when hot and/or cold water is drawn.
5. Higher cooling COP of the HP – enhanced by 2.22 to 10.66 % when hot and/or cold water is drawn, and reverts back to normal level when these utilities are not tapped.
6. Overall COP is very high – in the range of 2.25 to 2.49.
7. Clean–in–place heat exchangers – novel heat exchanger allows water passages to be cleaned without opening the HP casing.

Conclusion

A heat pump (HP) was developed at RAC Laboratory, P.V.P. Institute of Technology Budhgaon, which is capable of catering to air conditioning, heating tap water to 45°C and cooling potable water to 22°C. Heat Pumps have been designed to cater to the domestic and the light commercial market with nominal air conditioning capacity of 1, 1.5 and 2 TR in window and split models.

The test results for window in different modes shows that the cooling capacity is increased by 3.9 to 12.19 % and the cooling COP is enhanced by 2.22 to 10.66 % compared to conventional air conditioning systems. Performance of the Heat Pump reverts to that of conventional ACs when hot and cold water is not tapped.

Payback period for the Heat Pump works out to be 6.2 months for the commercial application without accounting for 100% depreciation available for these energy saving devices. Cost of the Heat Pumps will actually work out to be lower than that of conventional Window Air Conditioners /Split Air Conditioners + Electric water heater option. Thus, the user can benefit from both, lower initial cost and lower operating cost.

Economic analysis for a domestic application, where the unit cost is about Rs. 3/kWh as compared to Rs 6/kWh, will offer payback periods in the range of 12.2 to 12.4 months.

Hence the Window HPs can be used effectively for both residential and commercial purposes. These Heat Pumps can also prove to be very attractive for industrial applications when properly engineered.

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