GREEN TECHNOLOGIES RELATED TO REFRIGERATION AND AIR CONDITIONING

M V Rane
Professor and Energy Technology Consultant
Heat Pump Laboratory, Department of Mechanical Engineering
Indian Institute of Technology, Powai, Mumbai 400 076 INDIA
ranemv@iitb.ac.in

ABSTRACT *-- Increase in refrigeration and air conditioning systems usage is resulting in increased demand for electricity. Rising cost of fuel and electricity along with increasing concern for environment are directing us to develop sustainable solutions. Judicious application engineering along with the use of exhaust heat recovery heat exchangers and heat pumps can helps in co-generating various utilities like electricity, air conditioning, refrigeration, hot water, chilled potable water, dehumidifying and drying. This can reduce initial and operating cost of these utility generators. Reduced primary energy usage also helps in favorably addressing the global warming issue. This paper presents some such case studies for co-and tri-generating various cold and hot utilities using innovative designs of Matrix and Tube-Tube Heat Exchangers and Multi-Utility Heat Pumps developed at Heat Pump Laboratory in IIT Bombay (HPL_IITB). Techno-economic benefits of some of these installations deployed in domestic, industrial and commercial applications are discussed. Attractive paybacks, in the range of 3 to 18 month, are achieved in most of the cases with proper application engineering. Various opportunities for utilizing the surplus hot utility for dehumidification using liquid desiccants are also briefly discussed.*

Key words*: Matrix, Tube-Tube, Heat Exchanger, Heat Recovery, Heat Pump, Cogeneration*

1. INTRODUCTION

Globalization and rising standards of living is increasing the demand for refrigeration and air conditioning. Generation of heating, refrigerating and air conditioning utilities typically account for 40 to 70% of the electrical power consumed in various domestic, commercial and industrial sectors. Meeting the peak demand of electricity with limited generation and transmission infrastructure has been a challenge. Increasing energy costs, concern for the environment and fast depleting conventional sources of fuel are forcing us to review conventional practices and develop sustainable and greener ways of meeting our requirements.

Resorting to appropriate specifications for the required utilities and then optimally designing systems to cater to the requirement of various cold and hot utilities will help in addressing sustainability. Energy cost reduction has become essential in order to compete 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 electricity, cold and hot utilities will reduce energy consumption and associated cost. Recovering heat from the exhaust and engine cooling circuits of generating sets, engines and gas turbines, and using it for coproducing various hot and cold utilities is theoretically a very attractive proposition. Similarly opportunities exist for recovering heat from existing air conditioning and refrigeration systems, and using it to meet the demand for hot water, drying, dehumidifying, etc., in various residential, commercial as well as industrial applications.

Heat pump is also a device which can be used to deliver cold and hot utilities (Seo, (2000), Rane and Gupta (2001), Rakhesh et al. (2003), Lam and Chan (2003)). Patented Multi-Utility Heat Pumps (MU_HP) can simultaneously cater to cooling and heating requirements while reducing the input energy, Rane and Das Gupta (2003). Proper application engineering is a key to reducing energy usage and associated cost.

Paying attention to component efficiencies (Szargut, 2002) and developing suitable delivery mechanisms like radiant heating and cooling panels (Kilkis, 2006) will help improve overall system efficiency further.

MU_HP is a device which pumps heat from, one or more low temperature source/s to one or more high temperature sink/s simultaneously, with the help of an external source of energy. MU_HPs can be of various types, viz. vapour compression, thermoelectric, absorption, adsorption and ejector. Vapour compression heat pump is driven using electrical energy or shaft power as input energy, while the energy input to the absorption, adsorption and ejector type heat pumps is in the form of heat. This heat can be obtained by direct burning of fuel or by recovering heat from various waste heat sources.

Safe, service free and reliable integration of MU_HPs depends to a great extent on the heat exchangers used to transfer heating and cooling effect from the refrigerant in the MU_HP and the process fluids/utility streams. Several challenges, with respect to reliability of operation, durability of the equipment, meeting the constraints of space, weight and cost, have restricted tapping into these opportunities.

Several patented technologies, like the Matrix Heat Recovery Unit (M_HRU), Rane (1999), for exhaust heat recovery, Tube-Tube Heat Exchanger (TT_HE), Rane and Tandale (2002), for heat recovery and exchange using a reliable vented double wall construction, and Multi-Utility Heat Pump (MU_HP), Rane and Das Gupta (2003) are some examples of technologies which have opened up the possibilities to encash the above listed opportunities. Proper application engineering is essential to ensure success in saving initial and/or operating cost while simultaneously being environment friendly.

This paper presents some such opportunities for co-and tri-generating various cold and hot utilities along with electricity using Matrix Heat Recovery Units (M_HRU), Tube-Tube Heat Exchangers (TT_HE) and Multi-Utility Heat Pumps (MU_HP) developed at Heat Pump Laboratory in IIT Bombay (HPL_IITB). Techno-economic benefits of these MU_HPs deployed in domestic, industrial and commercial applications are discussed.

2. MATRIX HEAT RECOVERY UNITS, M_HRU: Engine Exhaust Heat Recovery

M_HRU technology relates to an improved heat exchanger which can be used for recovering heat from engine exhaust to enable co-generation of hot and/or cold utilities/y with electricity.

A novel heat exchanger has been developed and commercialized which has several desirable features and has opened up several possibilities for it use. It consists of plurality of tubes/pipes for hot gases and plurality of tubes/pipes for the Heat Recovery Fluid, HRF. Conducting matrix encapsulates the tubes/pipes carrying hot smoke gases and heat recovery fluid in the shell with endplates and smoke boxes to form a matrix heat recovery module. M_HRU can be used to recover heat from hot gases and/or vapours. High gas velocities through straight tubes/pipes reduce fouling. Conducting matrix ensures good thermal contact between hot gases and heat recovery fluid and avoids hot spots. Heat recovered can be in the form of steam, hot water or hot thermic fluid, hot air, etc.

The M_HRU combines the advantages of smoke tube and water tube heat exchanger into a single unit, which leads to several advantages. Features, applications, benefits, etc. are listed hereafter.

Features

- ✓ ***Simple Design:*** *gases pass through straight tubes without fins*
- ✓ ***Modular Design with Wide Selection Range:*** *50 to 500 kW modules*
- ✓ ***Larger Heat Recovery Units with Multiple Modules:*** *no upper limit*
- ✓ ***High Heat Transfer Coefficients:*** *25 to 75* $W/m^2.K$
- ✓ ***Low Gas Side Pressure Drops:*** *75 to 150* mmH_2O
- ✓ ***On Line Continuous Cleaning:*** *options available*
- ✓ ***Low Fouling:*** *flue gas velocity optimized to prevent fouling*
- ✓ ***Compact Design:*** *1/3 the size of conventional smoke tube designs*
- ✓ ***Low Cost:*** *20 to 25% lower than that of conventional designs*
- ✓ ***Quick Steaming:*** *within 5 to 15 minutes from cold start*

Applications

- ✓ ***Water Heating:*** *up to 90 C (unpressurised) and up to 180 C (pressurised)*
- ✓ ***Steam Generation:*** *up to 20 bar*
- ✓ ***Thermic Fluid Heating:*** *up to 330 C*
- ✓ ***Furnace Oil Heating:*** *up to 130 C*
- ✓ ***Ammonia Generating:*** *up to 180 C*
- ✓ ***Air Heating:*** *up to 230 C*

Heat Sources

- ✓ ***Engine/Diesel Generator Exhaust:*** *300 to 660 C*
- ✓ ***Boiler/Furnace/Oven Exhaust:*** *210 to 660 C*
- ✓ ***Gas/Biogas Turbine Exhaust:*** *450 to 630 C*

Impact on Fuel Usage

- ✓ ***Diesel Gensets:*** *up to 25% Increase in Overall Energy Recovery*
- ✓ ***Gas/Biogas Turbine Exhaust:*** *45 to 60% of LCV of Fuel Recovery in the form of Usable Heat*

Economic Benefits

- ✓ ***Low Exchanger Cost:*** *Heat Recovery Units may have Lower Initial Cost Compared to Oil Fired Systems*
- ✓ ***Low Installation Charges:*** *Built-In By-Pass can be Provided as an Option to Reduce On-Site Duct Work*
- ✓ ***Low Payback Periods:*** *Usually in the Range of 6 to 12 months*

Figure 1: Matrix Heat Recovery Unit for Steam Generation
for Installation on a 1250 kVA Genset

While about 48 M_HRU have already been deployed in various industries on engines in the range of 165 to 6000 kW_e electric generating capacity to improve energy efficiency and reduce the CO_2 emissions, these compact and light weight M_HRUs can also be used to cost effectively recover heat from the exhaust gases of numerous gensets, automobile, trawler, ship engines and co-generate hot or cold utilities along with power. These can be used to build techno-economically viable distributed tri-generation systems based on post-harvest biomass based biogas and biofuels.

Tri-generation systems deployed around the periphery of our villages can cater to the essential electrical needs for lighting, communication, etc; while the co and tri-generated hot and cold utilities can take care of the refrigeration, cold store and/or milk chilling requirements along while supplying hot water, steam and/or drying utility to small and medium scale agro industries.

3. TUBE-TUBE HEAT EXCHANGERS, TT_HE: Vented Double Wall Heat Exchanger

This novel vented double wall Tube-Tube Heat Exchanger (Rane and Tandale, 2002) enables exchange of heat between multiple streams. Concern of accidental mixing of the fluids exchanging heat is put to rest with this versatile and reliable heat exchanger.

A tube-tube heat exchanger (TT_HE) is a double wall tubular heat exchanger wherein two or more tubes are placed side-by-side and bonded thermally using thermal bonding material (TBM) for effective transfer of heat. Use of bends and straight lengths in tube-tube heat exchanger results in significant enhancement in heat transfer due to secondary flows induced in the bends. The secondary flows induced in bend leads to heat transfer enhancement in bend as well as in straight length downstream of bend without significant increase in pressure drop.

Tubes are placed side-by-side in the TT_HE. Hence, diameter of tube replacing the outer tube of a tube-in-tube heat exchanger can be smaller. Tube diameter and number of tubes on each side can be chosen independent of each other, eg. 1-1, 2-1, n-n or n+1-n configurations are possible (Figure 2), resulting in greater flexibility in design.

<u>Features of TT_HE</u>

- ✓ ***Cost and Weight of Vented Double Wall Heat Exchangers is Low:*** *Having two sets of tubes side-by-side reduces weight and cost of tubes, as compared to one set inside the other in tube-in-tube heat exchangers and three tube sets in case of vented tube-in-tube heat exchangers*
- ✓ ***Size and Fluid Hold-Up is Reduced without Increasing Pumping Power:*** *Flexibility in choosing tube layout and size to maintain suitable flow regimes throughout the length of the flow passage*
- ✓ ***Enabling Compact and Cost Effective Multi-Stream Heat Exchangers:*** *Three to five stream heat exchanger can also be conveniently managed in a single heat exchanger, with reduced number of headers*
- ✓ ***Enabling Better Taping of Availability while Exchanging Heat:*** *Possibility of providing intermediate headers for introduction or extraction of partially heated or cooled streams*
- ✓ ***Ability to Handle Fluids with Particulate Matter and Fibrous Material:*** *Sooth tubes with bends of appropriate dimensions having no stagnation points*
- ✓ ***Possibility of Capacity Modification:*** *Modules can be added or removed*
- ✓ ***Uninterrupted Service and Ease of Maintenance:*** *Online cleaning of individual modules is possible using chemical descaling technique*

Exchanging heat between more than two fluid streams simultaneously in a single heat exchanger is now possible.

Introduction and extraction of a fluid stream at an intermediate point in a heat exchanger allows greater flexibility and possibility of better heat integration in various complex applications in chemical and refinery applications.

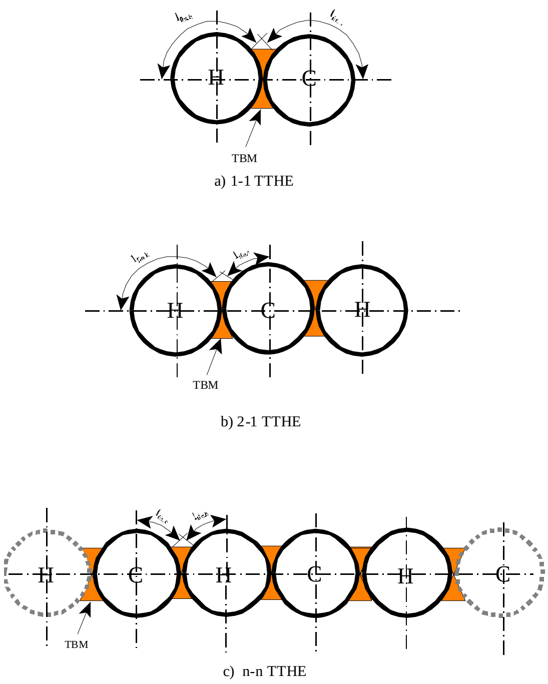


Figure 2: Sectional View of Three TT_HE Configurations

TT_HE can be used for heat recovery from engine cooling circuit, gas turbine lube oil cooling, desuperheating in refrigeration and air conditioning, dairy, and pharmaceutical industry, chemical industry, refinery, etc. They can also be deployed to recover heat from air compressors in the form of hot water and use it to vaporize liquefied petroleum gas, LPG, used in industries.

TT_HEs used as Superheat Recovery Water Heaters, SHR_WH, and in Heat Pump Water Heaters, HP_WH, will be a boon to the Agro-Processing Industry which has revenue generation potential comparable to that of the IT Industry. Cost effective on-farm agro-processing, cooling and drying, will increase the earnings of the rural masses.

Simulation programs, has been developed to design and optimize TT_HEs for various applications. The programs have about 120 input parameters and generates over 240 output parameters. The parameters enable the designer to account for space constraints, MOC preferences and operating temperatures/pressure drops, while optimizing cost.

TT_HEs are successfully demonstrated as superheat recovery water heaters, condenser/evaporator in heat pumps, lube oil cooler for shipboard gas turbines, milk/juice/potable water chilling and pasteurizing application.

Recovering heat from cold store refrigeration systems and using it for drying and dehumidifying agro and herbal products can make operation of cold stores economically very attractive.

<u>Super Heat Recovery-Water Heater, SHR_WH</u>: One of the ways of improving efficiency of space conditioning and water heating systems is to use desupeheater or SHR_WH with air conditioners, chillers, refrigeration systems and heat pumps. SHR_WH heats water using superheat in the compressed refrigerant coming out of the compressor. Figure 3 shows a schematic of the refrigeration system with a SHR_WH.

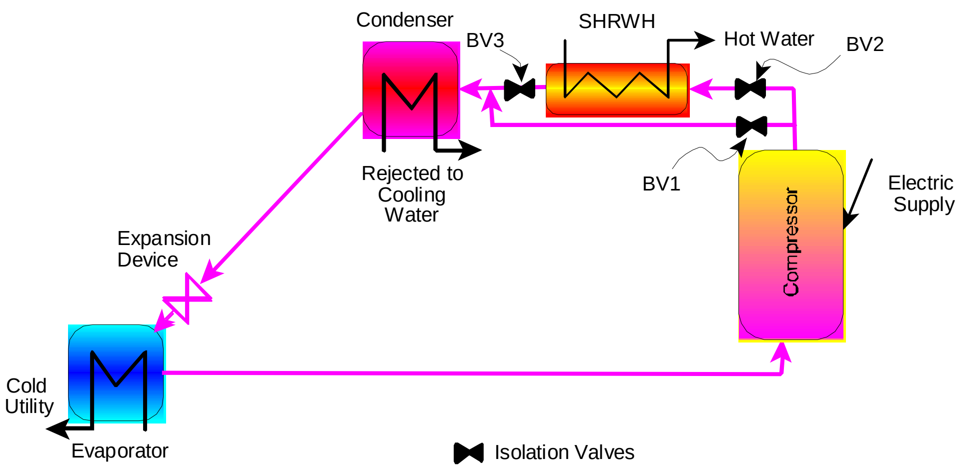


Figure 3: Refrigeration Circuit with Super Heat Recovery-Water Heater

Performance of air conditioner, chiller, refrigeration system and heat pump improves significantly when a SHR_WH is appropriately designed and integrated. While the recovered heat is free, the power consumption may reduce by 5 to 15% and the cooling capacity may increase by 5 to 10%. Hot utility may be generated when the refrigeration system is on and stored if it is required at a later time. More than 100 such installations based on the TT_HE technology are reliably operating. About 90 of these are installed in a chain of a multinational fast food restaurant.

SHR_WH reduces the load on existing condensers, which results in reduced condenser pressure, increased subcooling at the outlet of the condenser and thus, leads to increased cooling COP and capacity.

TT_HE based SHR_WHs have proved to be reliable and service free. Some of them have been operating for over eight years without a single service call. There are specific advantages of using this design. The main features of this design are listed below.

- ✓ ***Modular Design:*** Vented tube-tube design, starting with 0.5 TR modules with increments of 1 and 5 TR, no upper limit for chiller/refrigeration system capacity.
- ✓ ***High Heat Transfer Coefficients:*** Novel tubular exchangers optimised for high heat transfer coefficients at low-pressure drops on water/refrigerant sides.
- ✓ ***Material of Construction:*** Wide choice of MOC, optimised based on the application, SS316L, SS316, SS304L, SS304, MS, CS, Cu, etc. There is no restriction on use of material for tubes. Any material depending on compatibility with the fluids can be used.
- ✓ ***Easy to Maintain:*** SHR_WH can be cleaned-in-place using Chemical Descaling Fluids while keeping the chiller on line and bypassing the desuperheater.
- ✓ ***Low Initial Cost:*** SHR_WH uses plain circular tubes without enhancements.
- ✓ ***Safe Integration in to the System:*** Vented design ensures no mixing of refrigerant and water, SHR_WH can be isolated while chiller is on line.
- ✓ ***Simple to Retrofit:*** Only the tube/pipe between compressor and condenser is tapped into to install the SHR_WH.

4. MULTI_UTILITY HEAT PUMPS, MU_HP: Simultaneous Heating and Cooling

A MU_HP is shown in Figure 3, it can be used to simultaneously cater to Air Conditioning (AC) requirement, along with Water Heating (WH) and Potable Water Cooling (PWC) needs. Tap water can be heated to a temperature between up to 60 C. This hot utility can be used for bathing, cooking, dish washing, drying, laundry, etc. Potable water can be cooled down to 15 C and be used for drinking. Condenser heat can be alternately used for drying clothes.

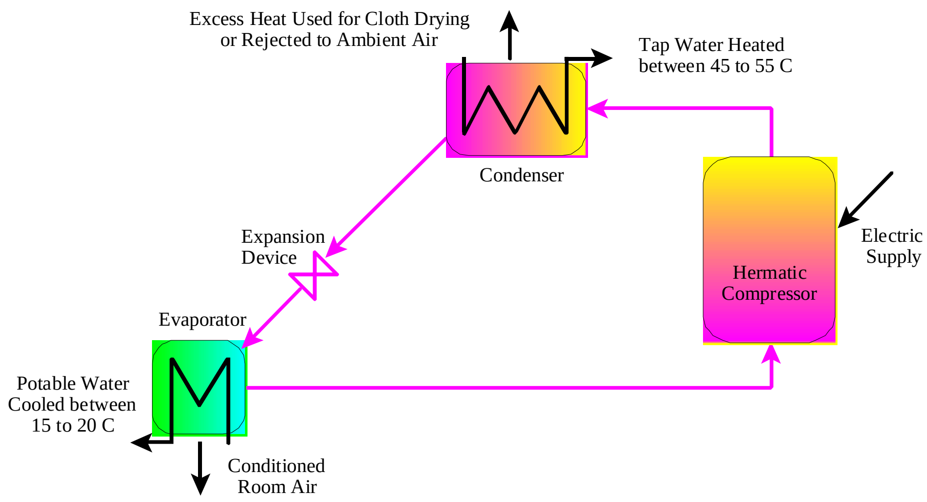


Figure 4: Multi-Utility Heat Pump for Domestic and Light Commercial Markets

In order to maximize overall COP, it is recommended to generate the hot utilities at the lowest usable temperatures and the cold utilities at the highest usable temperatures. Details of this type of MU_HP are reported in Rane and Gupta (2001). While the power consumption of the reported MU_HP of 1.5 TR cooling capacity was 1.8 kW_e based on eight year old technology, the latest 1.5 TR cooling capacity based MU_HP would consume only 1.5 to 1.55 kW_e. The reported MU_HP, which was built eight years ago, is still performing well at the author's residence.

MU_HPs can be of various configurations to suite the diverse applications with different proportions of hot and cold utilities needs. Proper application engineering is a key to the economic viability of the MU_HP installation. As will be seen from the case studies presented later in the paper, it will be possible to obtain simple payback in the range of 3 to 18 month in most of the applications.

MU_HPs can be classified based on the type of hot and/or cold utility generated or the type heat source and/or heat sink. Some variants of the MU_HPs are listed here:

Air to Air

- ✓ ***Cold Utility***: comfort air conditioning, cold store operation
- ✓ ***Hot Utility***: heating air for drying of clothes, agro products, regeneration of desiccants, etc

Air to Water

- ✓ ***Cold Utility***: comfort air conditioning, cold store operation
- ✓ ***Hot Utility***: heating water, direct heating of process fluids like cleaning solutions in industrial washing machines, drying agro products, regeneration of desiccants which can be used for taking care of latent cooling load, etc

Water to Water

- ✓ ***Cold Utility***: comfort air conditioning, precooling of fresh fruits, vegetables or flowers, direct process fluid cooling# in chemical, pharmaceutical and food processing industry
- ✓ ***Hot Utility***: heating water, direct heating of process fluids like cleaning solutions in industrial washing machines, drying agro products, regeneration of desiccants which can be used for taking care of latent cooling load, etc

Water to Air

- ✓ ***Cold Utility***: comfort air conditioning, precooling of fresh fruits, vegetables or flowers, direct process fluid cooling in chemical, pharmaceutical and food processing industry
- ✓ ***Hot Utility***: space air heating, heating air for drying of clothes, agro products, regeneration of desiccants, etc

Direct heating or cooling of process fluid is possible with the use of vented double wall TT_HE. More than 15 industrial MU_HPs are operational in industrial application of heating engine component cleaning solution in the industrial washing machines. The cleaning solution is typically heated between 50 to 60 C while simultaneously cooling the shop floor air or chilling water from 12 to 7 C for air conditioning application.

Heating capacity of these MU_HPs have been in the range of 18 to 48 kW. Reliable and trouble free operation has been demonstrated for over three years while heating cleaning solution with 3 to 5% oil in it and which also has suspended metal particles. Most of the conventional evaporators and condensers are not suitable for handling such fluids. Some of these MU_HPs are also co-generating potable chilled water used for meeting the drinking water needs on the shop floor.

Heat interactions in the evaporator and the condenser can be with multiple sources and sinks respectively. This enables generating multiple cold and/or hot utilities simultaneously. It also gives greater flexibility to fully tap the benefits of a heat pump. Figure 3, shows one such configuration where the evaporator caters to the potable water cooling and air conditioning needs while the condenser caters to hot water and clothes drying needs. Its allows partial recovery of heat from the compressed refrigerant, like in the case of Super Heat Recovery Water Heaters (SHR_WH), without penalizing the cooling COP. In fact SHR_WH help increase cooling coefficient of performance (COP) and capacity. If neither hot water nor clothes drying is required the excess condenser heat is rejected to ambient air.

Ground coupling of heat pumps gives advantages of higher heat source temperatures during the heating season and lower heat sink temperatures during the cooling season. This leads to increased COP and thus lower energy and operating costs.

5. VARIOUS APPLICATIONS OF MU_HP

MU_HPs can find applications in various segments of the HVAC&R market:
Residential Segment: Individual Homes, Bungalows, Housing Societies, etc
- ✓ *Cold Utility*: air conditioning and potable water cooling
- ✓ *Hot Utility*: heating water for bathing, dishwashing, washing machine input

Commercial Segment: Restaurants, Hotels, Health Clubs, Spas, Hospitals, etc
- ✓ *Cold Utility*: air conditioning and potable water cooling
- ✓ *Hot Utility*: heating water for bathing, sanitation, etc

Industrial Segment: Dairy, Pharmaceutical, Textile, Food Processing and Cold Stores, Automobile, etc
- ✓ *Cold Utility*: air conditioning, process cooling and potable water cooling
- ✓ *Hot Utility*: process heating, boiler feed water preheating, drying, liquid desiccant regeneration, etc

6. APPLICATION ENGINEERING

Objective of increasing energy efficiency and reducing operating cost needs to be achieved while simultaneously ensuring high reliability, simplicity of operation and ease of maintenance. The system should preferably be compact and have low initial cost or have a short payback period. Integration of new systems should be done with care. Fail safe integration in to the main plant operation should be ensured to eliminate the risks of any new technology introduction. Conventional utility generators may be left intact till full confidence is developed with any new technology. Use of the vented double wall Tube-Tube Heat Exchangers (TT_HE) help minimize the risks of leakage and mixing of the refrigerant and process fluids.

Design Should be Arrived at After Giving Due Consideration to
- ✓ ***Variation in Load Patterns:*** *design cooling, heating and/or drying dehumidification loads*
- ✓ ***Specific Process Requirements:*** *mode of heat recovery, in the form of potable hot water, boiler feed water, direct heating of process fluids or sea water for desalination, regeneration of liquid desiccant*
- ✓ ***Water Quality:*** *passage dimensions*
- ✓ ***Concept and Culture of Maintenance:*** *reflects on water passage dimension*
- ✓ ***Choice of Wetted Material:*** *Tube MOC has to be appropriately selected and wall thickness is to be determined based on corrosion characteristics and expected life*

Variables that Play an Important Role in Design Optimization
- ✓ ***Pressure Drop on Refrigerant Side:*** *affects size, weight and cost; specially capacity of the chiller/refrigeration unit may reduce if not designed properly*
- ✓ ***Refrigerant Velocities:*** *oil return and heat transfer coefficients*
- ✓ ***Water Velocities:*** *fouling, heat transfer coefficients and pumping costs*

Multi-Utility Heat Pumps: If super heat recovery opportunities do not exist, then a dedicated MU_HPs may be considered to cater to the hot utility generation requirement. If electricity is used to generate the hot utility, and the hot utility temperature is below 55 C, then the MU_HP is surely going to have an attractive payback, since it would be consuming only about 20 to 33% power. It may even be a lower initial cost option as compared to conventional electric heating used to generate the hot utility and conventional air conditioners, refrigeration system, chillers and or water coolers used to produce the cold utilities. Some case studies are included here.

Table 1: Case Study for Super Heat Recovery Water Heater, SHR_WH
Installation at a Hotel in Mumbai

Refrigeration System Capacity *Water Cooled Chiller with R22York Reciprocating Compressor*	***60 TR (211.2 kW_c)***
Temperature of Refrigerant, In / Out *Temperature of Water, In / Out* *SHR_WH is installed in counter-current mode*	*95 / 63 C* *30 / 60 C*
Total Capital Cost of Retrofit Installation *Includes installation and commissioning, taxes, etc*	***Rs 3 Lakh***
Hot Water Usage	***870 lph***
Heat Duty of SHR_WH, Q_h *30 kW_h / [(60 - 30) C x 4.18 kJ/kg.C] = 870 L/h water heating*	***30 kW_h***
Saving of High Speed Diesel, HSD, Required for Operating the Boiler *30 kW_h / (40337 kJ/l x 75% / 3600 s) @ CV 40337 kJ/l, boiler eff 75% & Rs 36 /l HSD*	***3.57 l/h***
Saving in HSD for Operating the Boiler *Site Data*	***81 l HSD/day***
Hour of Operation of WW MU_HP *@ 81 l/d / 3.57 l/h = 22.3 h/d*	***22.7 h/day***
Cost of HSD Saved *@ 36 Rs/l x 81 l/d = Rs2,916/d*	***Rs 2,916/day***
Annual Savings in HSD Cost *Assuming 360 d/yr and 80% occupancy Rs 2,916/d x 360 d/yr x 0.8 occupancy = Rs 8.4 Lakh*	***Rs 8.4 Lakh***
Simple Payback** **Considering 80% Depreciation in the First Year *Rs 3 Lakh x (1 – 0.8 x 0.35) / Rs 8.4 Lakh/yr = Rs 2.16 Lakh / Rs 8.4 Lakh/yr = 3.09 month* *Note: Increased cooling capacity is not taken credit for, this will make payback even more attractive*	***~3 month***
Reduction in CO_2 Emissions *Assuming 2.82 kg CO_2/L HSD Consumed* *CO_2 Emission Reduction = 81 L HSD /d x 2.82 kg CO_2/L HSD @ 360 d/yr x 0.8occupancy = 66 T/yr* *CO_2 Emission Reduction is increased by another 4 T/yr due to20% improvement in cooling COP*	***~550 tonne** since 2002*

Table 2: Case Study for Super Heat Recovery Water Heater, SHR_WH

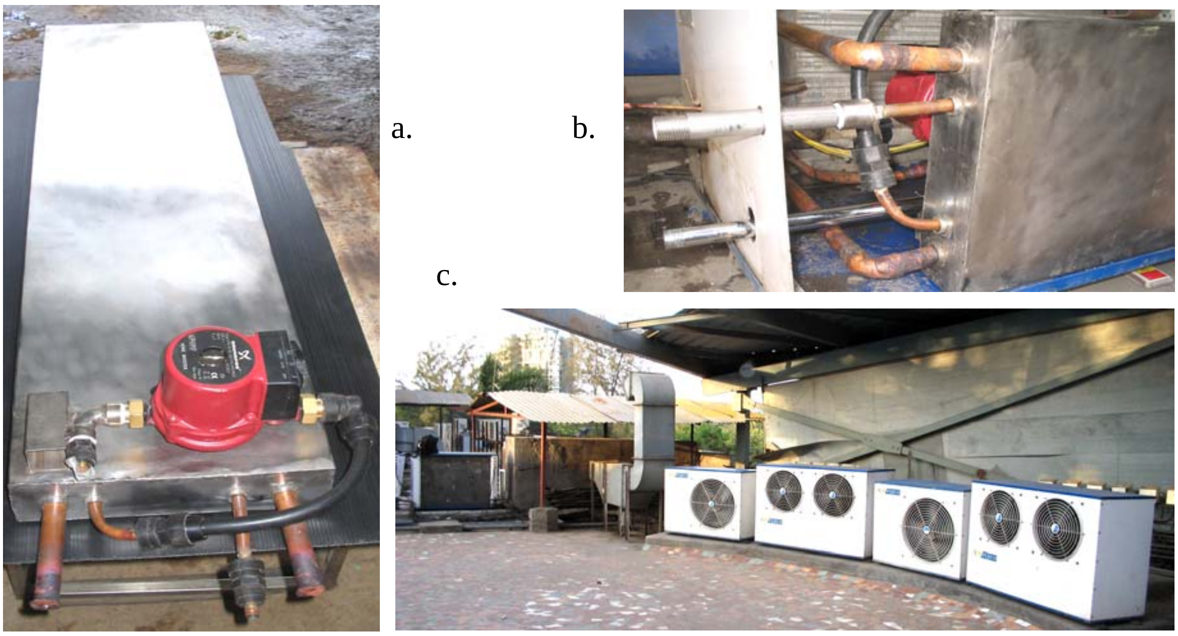
Installation at a Dairy in Mumbai

Refrigeration System Capacity *R717 Kirloskar Reciprocating Compressor*	***270 TR (950 kW_c)***
Temperature of Refrigerant, In / Out *Temperature of Water, In / Out* *SHR_WH is installed in counter-current mode*	*115 / 60 C* *30 / 75 C*
Total Capital Cost of Retrofit Installation *Includes installation and commissioning, taxes, etc*	***Rs 20 Lakh***
Hot Water Usage	***70,000 lpd***
Heat Duty of SHR_WH, Q_h *174 kW_h / [(75 - 30) C x 4.18 kJ/kg.C] = 3,330 L/h water heating*	***174 kW_h***
Saving of Furnace Oil, FO, Required for Operating the Boiler *174 kW_h / (40337 kJ/l x 80% / 3600 s) @ CV 40337 kJ/l, boiler eff 80% & Rs 27 /l FO*	***19.4 l FO/h***
Saving in FO for Operating the Boiler *Site Data*	***390 l FO/day***
Hour of Operation of SHR_WH *@ 390 l/d / 19.4 l/h = 20.1 h/d*	***20.1 h/day***
Cost of FO Saved *@ 27 Rs/l x 390 l/d = Rs10,530/d*	***Rs 10,530/day***
Annual Savings in FO Cost *Assuming 360 d/yr, Rs10,530/d x 360 d/yr = Rs 37.9 Lakh*	***Rs 37.9 Lakh***
Simple Payback** **Considering 80% Depreciation in the First Year *Rs 20 Lakh x (1 – 0.8 x 0.35) / Rs37.9 Lakh/yr = Rs 14.4 Lakh / Rs 37.9 Lakh/yr = 4.6 month* *Note: Increased cooling capacity by 5% and saved power consumption of one of the four condenser cooling water pumps is not taken credit for, this will make payback even more attractive*	***~4.6 month***
Reduction in CO_2 Emissions *Assuming ~2.82 kg CO_2/L FO Consumed* *CO_2 Emission Reduction =390 L HSD /d x ~2.82 kg CO_2/L FO @ 360 d/yr = 396 T/yr* *CO_2 Emission Reduction will be higher due to 5% improvement in cooling COP and saving in power of one of the four condenser cooling water pumps of 40 hp.*	***~385 tonne/yr** since 2003*

Table 3: Case Study for Super Heat Recovery Water Heater, SHR_WH

Installation at a Fast Food Outlet in Mumbai

Refrigeration System Capacity *Ductable Split AC (DS_AC) with R22 Scroll Compressor*	***8.3 TR (29.2 kW$_c$)***
Temperature of Refrigerant, In / Out	*115 / 60 C*
Temperature of Water, In / Out *SHR_WH is installed in counter-current mode*	*30 / 63 C*
Total Capital Cost of Retrofit Installation *Includes SS304 storage tank, insulation, piping, installation and commissioning, taxes, etc*	***Rs 1.2 Lakh***
Hot Water Usage	***1,000 lpd***
Fuel Saving, LPG *1000 lpd x 4.18 kJ/kg.C x (60 – 27) C / (42000 kJ/kg x 0.70) = 137,900 kJ/d / 29,400 kJ/kg LPG = 4.69 kg LPG/d* *@ CV 42000 kJ/kg, boiler eff 70%*	***4.69 kg LPG/day***
Saving in LPG Cost *4.69 kg/d /Rs 42/kg LPG = Rs 197/d*	***Rs 197/day***
Saving in Electricity Cost *@ 12 h/d operation, Rs 10/kWh$_e$, , 1.36 kW$_e$ DS_AC power saving and 0.75% loading* *1.36 kW$_e$ x 12 h/d x 0.75% loading x Rs 10/kWh$_e$, = 12.24 kWh/d x Rs 10/kWh$_e$,= Rs 122.4/d*	***Rs 122/day***
Saving in Operating Cost	***Rs 319/day***
Annual Savings in Operating Cost *assuming 360 d/yr*	***Rs 1.15 Lakh***
Simple Payback** **Considering 80% Depreciation in the First Year *Rs 1.2 Lakh x (1 – 0.8 x 0.35) / Rs 1.15 Lakh/yr = Rs 86,400/- / Rs1.15 Lakh/yr* *Note: Increased cooling capacity is not taken credit for, this will make payback even more attractive*	***~7.5 month***
Reduction in CO_2 Emissions *Assuming 0.804 kg CO_2/kWH Electricity Consumed & ~3 kg CO_2/kg LPG Consumed* *CO_2 Emission Reduction = (4.69kg LPG /d x3 kg CO_2/kg LPG + 12.24 kWh/d x 0.804 kg CO_2/kWh) @ 360 d/yr* *CO_2 Emission Reduction = (14.07 + 9.84) kg CO_2/d = 23.91 kg CO_2/d @ 360 d/yr = 8.6 T/yr*	***~8.6 tonne/year***



a. b. c.

a. SHR_WH with hot water circulation pump
b. SHR_WH installed and piped inside the outdoor condensing unit of a 8.3 TR Ductable Split AC
c. View form outside: second unit from the left has the SHR_WH

Free Water Heating 240 lph, Water Heated from 27 to 60 C, AC Power Saving 12 to 15.6%

Figure 3: Super Heat Recovery Water Heater, SHR_WH

Installation at a Fast Food Outlet in Mumbai

Table 4: Case Study for a Multi-Utility Air to Water Heat Pump, AW_HP
Installed at an Automobile Manufacturing Unit

Utilities Produced by AWW MU_HP	***ESH***	***MU_HP***
Synclean Solution Heating from 50 to 55 C	*75 kW*	*48 kW*
Air Conditioning		*8.5 TR (30 kW_c)*
Potable Water Cooling		*4.1 kW*
Power Consumed	***ESH***	***MU_HP***
Electric Solution Heater, ESH *2 h preheating @ 100% duty and 8 h @ 60% duty cycle*	*75 kW*	
AWW Multi Utility Heat Pump, MU_HP		*18 kW*
Solution Pumps *3 h preheating @ 100% duty and 8 h @ 94% duty cycle*		*1 kW*
Total Power Consumption	*510 kWh/day*	*200 kWh/day*
Reduction in Power Consumption		*61%*
Total Operating Cost *@ 5 Rs/kWh*	*2550 Rs/day*	*880 Rs/day*
Saving in Operating Cost		***1370 Rs/day***
Heat Duty of AWW MU_HP, Q_h *for Cleaning Solution In/Out temperature is 50 / 55 C*		***48 kW_h***
Bonus Cooling Duty of AWW MU_HP, Q_c		***8.5 TR (30 kW_c)***
Cost of Electrical Power Used to Operate Cleaning Solution Heaters *75 kW x (2 h + 8 h x 60% duty cycle) x 5 Rs/kWh = (150 + 360) kWh/d x 5 Rs/kWh = 510 kWh/d x 5 Rs/d = Rs 2550 /d*		*Rs 2,550/day*
Cost of Electrical Power for AWW MU_HP *(18 +1) kW x (3 h + 8 h x 94% duty cycle) x 5 Rs/kWh = (57 + 143) kWh/d x 5 Rs/kWh = 200 kWh/d x 5 Rs/d = Rs 1000 /d*		*Rs 1,000/day*
Saving in Operating Cost		***Rs 1,550/day***
Annual Savings in Operating Cost *Rs 1550/d x 300 d/yr operation = Rs 4.65 Lakh*		***Rs 4.65 Lakh***
Total Capital Cost of AWW MU_HP Installation *Includes application engineering, piping, installation and commissioning, taxes, etc*		***Rs 10 Lakh***
Simple Payback *Considering 80% Depreciation in the First Year: Rs 10 Lakh x (1 – 0.8 x 0.35) / Rs 4.65 Lakh = Rs 7.2 Lakh / Rs 4.65 Lakh* ***Savings due to bonus utilities generated, if accounted, will lead to a payback of about 12 month for One Shift Operation***		***18.6 month***
Net Saving in Power Consumption		***310 kWh/day***
CO_2 Emission Reduction *Assuming 0.804 kg CO_2/kWH Electricity Consumed* *CO_2 Emission Reduction = 310 kWh/d x 0.804 kg CO_2 = 249.2 kg CO_2/d @ 300 d/yr = 74.75 tonne/yr*		***74.8 tonneCO_2/yr***
CO_2 Emission Reduction if Cold Utilities are Also Accounted *Additional CO_2 Emission Reduction due to Bonus Cold Utility = (30 kW_c/COPc 5) x (3 h + 8 h x 94% duty cycle) x 0.804 kg CO_2* *= (6 x 10.52) kWh/d x 0.804 kg CO_2 = 63.1 kWh/d x 0.804 kg CO_2 = 50.75 kg CO_2/d @ 300 d/yr = 15.2 tonne/yr*		***90 tonne CO_2/yr***
Peak Electrical Demand is Reduced from 75 kW to 19 kW		***75%***

Figure 4: Multi-Utility Air to Water Heat Pump, AW_HP
Currently Installed at an Automobile Manufacturing Unit

Table 5: Case Study for a Multi-Utility Water to Water Heat Pump, WW_HP
Installed at Hotel in Goa

Heat Duty of Water to Water MU_HP, Q_h *Hot Water In/Out temperature is 41 / 60 C* *36 kW_h / [(60 - 41) C x 4.18 kJ/kg.C] = 1632 L/h water heating from 41 to 60 C or* *36 kW_h / [(60 - 30) C x 4.18 kJ/kg.C] = 1034 L/h water heating from 30 to 60 C*	***36 kW_h***
Saving of High Speed Diesel, HSD, Required for Operating the Boiler *36 kW_h / (40337 kJ/l x 84% / 3600 s) @ CV 40337 kJ/l, boiler eff 84% & Rs 36 /l HSD*	***3.82 l/h***
Saving in HSD for Operating the Boiler *Site Data*	***85 l/day***
Hour of Operation of WW MU_HP *@ 85 l/d / 3.82 l/h = 22.3 h/d*	***22.3 h/day***
Cost of HSD Saved *@ 36 Rs/l HSD x 85 l/d = Rs 3,060/d*	***Rs 3,060/day***
Cooling Duty in the form of Chilled Water, Q_c *Chilled Water In/Out temperature is 12 / 7 C*	***24 kW_c (6.8 TR)***
Electrical Power Saving on Central Chiller *Assuming Existing Chiller COP of 5 Power Consumed = (24 kW_c / 5) x 22.3 h = 4.8 kW_e x 22.3 h = 107 kWh/d*	*107 kWh/day*
Electrical Power Supplied to the WW MU_HP *@ 12 kW_e x 22.3 h/d = 267.6 kWh/d*	*268 kWh/day*
Total Capital Cost of Water to Water MU_HP Installation *Includes application engineering piping, installation and commissioning, taxes, etc*	***Rs 7.2 Lakh***
Cost of Electrical Power Reduction on Chiller *Assuming Existing Chiller COP of 5 Power Consumed = (24 kWc / 5) x 22.3 h = 4.8 kWe x 22.3 h = 107 kWh/d* *Cost of operating conventional Chiller 107 kWH/d x 4 Rs/kWh = Rs 428 /d*	*Rs 428/day*
Cost of Electrical Power Supplied to the WW MU_HP *@ 12 kWe x 22.3 h x 4 Rs/kWh = Rs 1070/d*	*Rs 1,070/day*
Cost of Net Increase in Electrical Power Consumption *Heat Duty and Electrical Power Saving will Increase Further* *If hot water temperature is reduced from 60 to 55*	***Rs 642/day***
Cost of HSD Saved *@ 36 Rs/L x 85 L/d = Rs 3,060/d*	***Rs 3,060/day***
Net Saving in Energy Cost, Fuel & Electricity	***Rs 2,418/day***
Annual Savings in Energy Cost *Assuming 230 d/yr of full occupancy*	***Rs 5.56 Lakh***
Simple Payback *Considering 80% Depreciation in the First Year* *Rs 7.2 Lakh x (1 – 0.8 x 0.35) / Rs 5.56 Lakh = Rs 5.18 Lakh / Rs 5.56 Lakh* *Cost of new installation can take credit for boiler cost, this will lead to a payback of about 6 to 9 month*	***~11 month***
Net Increase in Electrical Power Consumption *Power Consumed by WW_HP - Conventional Chiller = (267.8- 107) kWh/d = 159 kWh/d*	***159 kWh/day***
CO_2 Emission Reduction *Assuming 2.82 kg CO_2/L HSD and 0.804 kg CO_2/kWH Electricity Consumed* *CO_2 Emission Reduction = 85 L HSD /d x 2.82 kg CO_2/L HSD - 159 kWh/d x 0.804 kg CO_2/kWh* *CO_2 Emission Reduction = (239.7 - 127.8) kg CO_2/d = 1119 kg CO_2/d @ 230 d/yr = 25.7 T/yr*	***25.7 tonneCO_2/yr***

As can be seen from the case studies, for SHR_WH, AW_HP and WW_HP there is ample scope for energy cost reduction and operating cost saving. Saving can be larger with MU_HPs, where utilization of the different utilities is significant.

There are various other ways of improving energy efficiency of air conditioning, chilling, refrigeration systems. Ground coupling of Heat Pumps to reject or receive heat from the ground, at least 3 m below the surface, can help reduce required temperature lifts across the evaporator and condenser, thereby increasing COP and energy efficiency. A 1 TR nominal cooling capacity, ground coupled heat pump is shown in Figure 5. The benefits may be summarized as about 10 to 25% increase in cooling capacity and 25 to 40% increase in COP when coupled with a 27 C ground coupled water source as compared to 34 C ambient air for heat rejection. The benefits realized would increase significantly as the ambient air temperature increases further to 45 C and beyond.

Nominal Cooling Capacity 1 TR, Cooling Duty Increase 26% , COP Increase 43%
Ground Water Loop 28.5 to 34.6 C @ 780 lph

Figure 5: Ground Water Couple-Air Conditioner, GWC_AC
Installed in Ahmadabad

Radiant cooling and heating panels can help increase the evaporator temperatures and lower the condenser temperature respectively in an air conditioning application. This has been demonstrated in a radiant panel cooled condenser of a small MU_HP used to cater to the water cooling needs of the Mechanical Engineering Department at IIT Bombay. Performance testing of first prototype Energy Efficient Instant Water Cooler (EE_IWC) was undertaken at the Heat Pump Laboratory. It has a cooling COP in the range of 1.3 to 2 with cooled water delivery in the range of 15 to 20 C.

EE_IWC stores the cooling effect without storing potable water. System has natural convection and radiant cooled condenser, which has potential to eliminate the need for noisy condenser fan and periodic cleaning of a fin tube condenser. Since, successful commissioning in December 2006, EE_IWC has been performing well without service. EE_IWC has provision to conceal aqua guard water purifier. One such cooler is capable of delivering cooled water even on floor higher than where the cooler is located. It also provided warm water along with cold water.

***Chilled Drinking Water* 50 lph**

Instant chilling effect 20 C

***Power consumption* 480 to 510 W**

Energy Efficient System with
Novel Design, Naturally Cooled Condenser

Ease of Servicing and Protection for Filter

Filtered Warm Water can also be Co-Generated

Figure 6: Energy Efficient – Instant Water Chiller, EE_IWC

Multi-Utility Heat Pumps, MU_HP, of small capacities, in the range of 0.75 to 5 TR, can also be used for on-farm pre-cooling of milk, fresh fruits and vegetables while simultaneously drying fruits, herbs or spices.

Heat required for low temperature drying is delivered free of cost, while simultaneously increasing the cooling capacity and coefficient of performance of the refrigeration system.

Recovered heat, in the form of hot water at 45 to 60 C or regenerated liquid desiccant can be used along with low cost plastic heat exchangers to dry various temperature sensitive products. Hot utility can be used to dry agro products to generate additional revenue. These types of systems will help reduce spoilage of perishables by increasing shelf life and significantly enhancing the earnings of the farmers through production of value added dried products.

7. IMPACT OF SUCCESSFUL DEPLOYMENT OF VARIOUS TECHNOLOGIES

Impact on energy usage will be as follows:

- ✓ ***Saving in fuel or electricity while co-generating hot utilities*** *using M_HRU, SHR_WH and HP_WH will be* ***over 90%***
- ✓ ***Saving in fuel or electricity to generate cooling effect*** *will be* ***5 to 20%***
- ✓ ***Saving in fuel or electricity while recovering waste heat*** *using TT_HW will be* ***over 90%***
- ✓ ***Peak electricity demand*** *for electric water heating will be* ***lowered by 95%***

Environment and ecological benefits will be as follows:

- ✓ *Saving in fuel and electricity will lead to corresponding* ***lowering of emissions***
- ✓ *Recovering waste heat will lead to* ***reduced thermal pollution***

Quality of life improvements in backward areas is possible due to increased earnings of the rural masses by cost effective on-farm agro-processing. Cost effective precooling of fresh fruits, vegetables, milk and horticulture products will help reduced wastage and improve quality of the products, which will increase the potential to tap the export market. Drying of grapes, onions, herbs, spices with the recovered free hot water will significantly improve value realized at the rural processing centres.

Direct employment generation to manufacture, retrofit and service SHR_HW and HP_WH along with substantial indirect employment generation in agro-processing units in rural areas for on-farm and forest based products will take place. Additional employment will be generated by collection, sorting/grading, cleaning, precooling/drying, packaging, activities associated with agro-processing.

8. CONCLUSIONS

Techno-economic benefits of the Matrix Heat Recovery Units, M_HRU, Superheat Recovery Water Heaters, SHR_WH, and Multi-Utility Heat Pumps, MU_HP, deployed in domestic, industrial and commercial applications are discussed. Generation of multiple hot and/or cold utilities simultaneously give added flexibility in matching the heating and cooling effects produced by MU_HPs. Attractive paybacks, in the range of 3 to 18 month, are achieved in most of the cases with proper application engineering.

Ground coupling along with radiant cooling or heating panels also offers avenues for significant energy saving. Various opportunities for utilizing the surplus hot utility for drying and dehumidifying using liquid desiccants are also briefly discussed. Revenue generated through recovered heat can more than pay for the cost of operating the cold utility generators!

Increasing energy costs and raising concern for environment heightens the need to go for heat recovery systems. Various reliable options are available; with Double Wall Vented Designs the worry of cross contamination is eliminated. Installations have been working satisfactorily for several years, in many cases without a service call.

Co-production of multiple utilities using a single system helps reducing space requirement, initial cost and maintenance. CO_2 emissions are also reduced and electrical demand reductions are also realized. Proper application engineering can ensure a Win-Win situation of simultaneously reducing initial and operating cost.

REFERENCES

Ji, J, Chow, T, Pei, G, Dong, J, He, W; (2003) “Domestic Air-Conditioner and Integrated Water Heater for Subtropical Climate”, **Applied Thermal Engineering**, 23 581-592.

Kilkis, B I; (2006) “Cost Optimization of a Hybrid HVAC System with Composite Radiant Wall Panels”, **Applied Thermal Engineering**, 26, 10-17.

Lam, J C, Chan, W W; (2003) “Energy Performance of Air-to-Water and Water-to-Water Heat Pumps in Hotel Applications”, **Energy Conversion and Management**, 44, 1625-1631.

Rakesh, B G, Venkatarathnam, Murthy, S S; (2003) “Experimental Studies on a Heat Pump Operating with R22, R407C and R407A: Comparison from an Exergy Point of View”, **Transactions of ASME**, 125, 101-112.

Rane, M V; (1998) "Energy Conservation in Refrigeration and Air-Conditioning”, **Air Conditioning and Refrigeration Journal**, Vol 1, No 1, pp 25 - 30.

Rane, M V; (1999) “An Improved Heat Exchanger in the Form of a Matrix Heat Recovery Unit”, **Indian Patent** # 196 527.

Rane, M V, Das Gupta, A; (2001) “Heat Pump for Domestic and Light Commercial Markets - Conditions Air, Heats Tap Water and Cools Potable Water”, **Air Conditioning and Refrigeration Journal**, Vol 4, No 1, pp 37 - 42.

Rane, M V, Das Gupta, A; (2003) “Multi Utility Vapour Compression System”, **Indian Patent** # 212 316.

Rane, M V, Kukreja, G; (1998) “Development of an Ammonia/Water Based Vapour Compression Heat Pump”, **Proceedings of IIR Conference on Emerging Trends in Refrigeration & Air-Conditioning**, New Delhi, INDIA, Mar 18 to 20, 1998.

Rane, M V, Tandale, M S; (2002) “Tube-Tube Heat Exchanger”, **Indian Patent** # 205 362.

Rane, M V, Tandale, M S; (2005) “Water-to-Water Heat Transfer in Tube-Tube Heat Exchanger: Experimental and Analytical Study”, **Applied Thermal Engineering**, Vol 25, pp 2715 - 2729.

Rane, M V, Tandale, M S, Tiwari, V; “Tube-Tube Heat Exchanger for Heat Recovery from Engine Cooling Circuit: Water Heating and Space Heating Applications”, **Proceedings of International Conference on Sustainable Habitat in Cold Climates**, Leh, IINDIA, Sep 16 to 18, 2004.

Rane, M V, Tandale, M S; “Benefits of Superheat Recovery on Chillers: Case Study for a Hotel Installation”, **Proceedings of International Congress of Refrigeration ICR 2003**, Washington DC, USA, Aug 17 to 22, 2003.

Seo, K, Kim, Y; (2000) “Evaporation Heat Transfer and Pressure Drop of R-22 in 7 and 9.52 mm Smooth/Micro-Fin Tubes”, **Int. J. Heat Mass Transfer**, 43, 2869-2882.

Szargut, J; (2002) “Component Efficiencies of a Vapour-Compression Heat Pump,” **Exergy, an International Journal**, 2, 99–104.