Making Energy Intensive HVAC Processes More Sustainable via Low Temperature Heat Recovery

David Sellers, Portland Energy Conservation Inc.
Tom Stewart, Memorial Hospital of Carbondale

ABSTRACT

This paper looks at low temperature hot water distribution and heat recovery as an approach that can be used in health care and laboratory applications to reduce the energy intensity of the HVAC reheat and preheat process. The concepts presented could easily be applied to reheat and preheat processes in other applications such as semiconductor and pharmaceutical clean rooms. The paper also looks at radiant slabs as an opportunity to use low temperature hot water for comfort heating applications in new construction. A case study of an application in a health care environment is included.

Introduction

Current air handling system configurations, such as Variable Air Volume (VAV) systems, have led to significant reductions in HVAC energy requirements in many applications. However, there are some applications that require precise control of the pressure relationships between adjacent spaces and precise control of the temperature and humidity at the load. These requirements often eliminate the VAV approach as an option and force designers to use a constant volume reheat system. Examples of such applications include surgical suites, laboratories, and clean rooms. The reheat process of these systems is typically very energy intensive since it often involves simultaneous heating and cooling. In addition, the large volumes of outdoor air required often result in significant preheat loads.

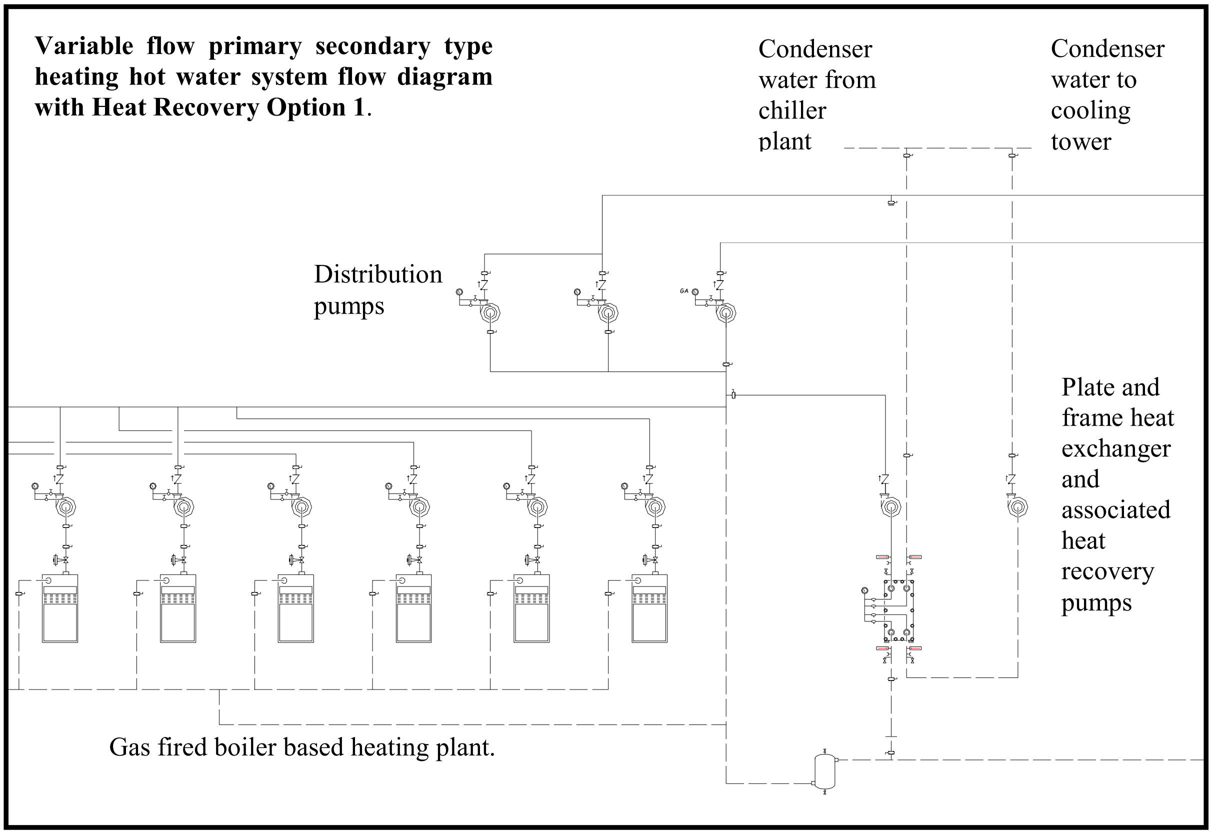
There are some characteristics of the preheat and reheat loads associated with these processes that make them ideal low heating water temperature loads. These characteristics are often complemented by the nature of the load served by the system since they typically represent very high internal gains, and are a source of recoverable heat. In new construction, radiant slabs can represent an opportunity to use this recovered energy for comfort heating in addition to the preheat and reheat processes.

The information presented in this paper is based on actual installations and experience with low temperature hot water systems in the context of a distribution and utilization strategy that is readily adaptable to recovered energy. An overview of technical considerations is followed by a case study of a low temperature hot water system at the Memorial Hospital of Carbondale, Illinois (MHC).

Technical Discussion

The following paragraphs explore some of the technical issues associated with low temperature hot water systems. Figure 1 illustrates a typical system configuration as extracted from schematic design documents for a project in the Northwest. The arrangement allows energy recovered from the condenser water to serve summer time and swing season reheat loads that exist on the project.

Figure 1. Typical Low Temperature Heat Recovery Application



Source: PECI, 2002

Minimize the Loads

This is an important first step in any process to improve efficiency. Serving a load with recovered energy is nice, but minimizing or even eliminating the load is even better. In some cases, recovering energy for use in another process eliminates an operating or parasitic load from the system in addition to a process load. For instance, recovering energy from the condenser water system to serve reheat loads eliminates the reheat load (process load). But, it also eliminates a portion of the parasitic load that is associated with rejecting the condenser heat to atmosphere because the cooling tower fans will run fewer hours. There is usually some trade-off required to accomplish this. For instance, there is usually extra pumping energy associated with the heat recovery process. But attending to the details of the design and being creative in the design approach can often result in a net reduction in parasitic loads in addition to the reduction in process loads associated with the actual energy recovery.

Advantages of Low Temperature Water

To recover energy, it is usually necessary to transfer it from the waste stream of one process to the supply stream of another with some physical separation in between the two.

This requires a temperature differential between the process stream that is the source of the energy and the process stream to which the energy will be transferred. Due to basic thermodynamic principles, the temperature of the supply stream might approach, but will never equal the temperature of the waste stream. Improving the approach usually involves purchasing more heat transfer surface, which typically has limits in terms of first cost and in terms of the impact the device has on the two process streams. Pressure drop is one example of this.[1]

Renewable heat sources are often constrained by similar considerations. Sometimes, this is because they are a byproduct of some other process (the hot water that comes off of an operating fuel cell for instance). In other cases, they suffer significant degradations in the efficiency of their collection mechanisms as their operating temperatures increase (for example solar collector efficiency drops significantly as the operating temperature increases).

In most cases, serving a heating load with the lowest possible supply temperature will pave the way for energy recovery and renewable resources, even if they do not provide the energy source immediately. A high-grade thermal resource can just about always be easily degraded to a lower thermal potential if necessary, usually with out the addition of energy.

Loads that are not initially served by renewable or recovered energy via a low temperature systems can offer some advantages in terms of first and operating costs. Because they operate at a lower temperature, the parasitic losses associated with them are lower. This can be a very significant factor on a large distribution system. For example, a bare 2” steel pipe located in a ceiling plenum that is running in the 80°F range carrying water at 80°F does not lose energy to the plenum. This same line at 280°F (the saturation pressure of steam at approximately 35 psig) will loose 280 btu/hr/ft (ASHRAE 2001) for portions where it or the fittings connected to it are uninsulated. With insulation, this value drops into the 30 btu/hr/ft range. This energy often shows up as a cooling load in addition to representing a parasitic loss from the heating plant.

In some instances, these minimal or non-existent parasitic losses can be translated into a first cost savings in addition to an operating cost savings. On one of the projects where a low temperature water system was employed, the insulation was eliminated from the distribution piping network because the piping spent no significant amount of time above the ambient temperatures of the areas that it ran in. Thus, there was no need for insulation as a practical matter nor from a code perspective.

Cautions Associated with Low Temperature Heating Water System Design

In some instances, a low temperature system may require a higher over-all flow rate than a system that is served with more conventional supply temperatures coupled with large differential temperatures on the loads. However, attending to the details of coil selection and load profile and designing to address the real needs of the system can mitigate the impact associated with this. Based on past experience, the following points apply:

- The nature of reheat loads and equipment used to serve them tends to result in low temperature drops at the coils regardless of the supply temperature. As a result, the

---

[1] In theory, mixing the two streams will preserve all of the energy content, but this approach is often undesirable or impossible from a process standpoint. And the resulting mixed stream will be at a thermal potential somewhere between the thermal potential of the two streams that are mixed initially.

flow rates required for a low temperature system as compared to a high temperature system are often not that different.

- The flow rates at the terminal equipment connections to reheat loads are often low relative to the 1/2 and 3/4 inch line sizes used to connect them to the system. Thus, a modest increase in flow rate often has no impact on the line size or first cost of the terminal equipment piping system.
- When system diversity is considered and the difference between the real load and design load is taken into account,[2] increases in flow that may show up at the individual terminal units often cancel each other out and the net system flow rate for the low temperature system and high temperature system are nearly identical for most of the operating conditions.
- Preheat loads served by low temperature water can be selected to take significant temperature drops under design conditions. It is not uncommon for a preheat load to require a leaving temperature somewhere in the mid 50's°F and with an entering air temperature in the 10-20°F range or lower. Under these conditions, temperature differentials of 30-40°F or more can be achieved between the supply and return connections. The larger differential associated with the preheat loads will help increase the over-all system differential temperature when it mixes with the return water from loads with lower differentials, like terminal equipment. This often improves the ability to recover energy at exactly the time when it is needed the most.
- Systems using recovered energy at low distribution temperatures may be designed to meet the loads for most of the operating hours. However, it would be poor engineering practice to assume that the recovered energy source would be available and of sufficient magnitude to meet the needs of the system under all operating conditions. Thus, back-up/supplemental capacity needs to be provided.
- Low temperature systems often operate on very low temperature differentials between the source of the heat and the process using it. This makes the operation and monitoring of the system more sensitive to sensor calibration and good heat transfer than a more conventional system. Degradations in sensor accuracy could actually lead to heat being transferred out of the process rather than into the process. Degradations in heat transfer performance will show up as operational issues much more quickly than in a conventional system. Thus, this type of system should be installed in an application where the Owner is committed to good operating practice and the staff is fully trained in the nuances of system operation.
- Incorporating low temperature water as a feature of a new design will almost always be economically more attractive than retrofitting it later. There are instances where significant (but potentially justifiable) costs will need to be incurred in order to realize the potential for low temperature energy recovery in an existing system. Had these projects included this approach as a design philosophy from the outset, the benefits would have been realized with little if any first cost penalty.

---

[2] The conditions that heating systems are designed to meet and the conditions that they actually operate under are often quite different. Most heating loads assume a worst case scenario that will seldom if ever occur; virtually no credit is taken for internal or solar gains, infiltration rates are assumed to be high, and it is assumed that the extreme condition persists to the point where the building structure is thermally saturated. While it is probably important to design the system so it can handle these conditions, it is probably more important to design the system to operate efficiently at the real world conditions it will see most of the time.

Renewable and Recoverable Energy Sources Suited to Low Temperature Applications

A primary goal of sustainable design is to "make use of all economically available differences in temperature from environmental conditions and facility processes before discarding them to the environment" (Rumsey). Previous discussions have alluded to many sources of renewable or recoverable energy that lend themselves to this application. At the low end of the scale, plate and frame heat exchangers often will allow water in the 88-93°F range to be generated directly from sources in the 95-100°F range like condenser water or low temperature solar collectors. In some instances a heat exchanger may not even be required to separate the source from the process, further improving the available supply temperature. This is particularly true for processes where the recovered energy is a byproduct of the process, like the warm water that is discharged by an operating fuel cell.

Heat pumps provide a mechanism for improving the thermal potential of a low temperature source by elevating its temperature with the input of energy. This can add complexity to the process but may be desirable if it makes the recovered energy more usable for more of the operating window. Typically, the energy put into the heat pump to raise the thermal potential of the recovered energy is also recovered. Best efficiencies will be realized by minimizing the differential at which the heat pump must operate.

Building Loads Adaptable to Low Heating Water Supply Temperatures

Many of the systems that are the subjects of this paper were targeted at serving domestic water loads, and air system preheat and reheat loads. In many ways, these loads are ideal low temperature heating water loads because the entering conditions to the heat transfer elements are typically in the 55°F range or lower and the leaving requirements are often in the 70-75°F range or lower.[3] These requirements can often be easily met with sources in the mid to upper 80°F range. The real challenge in low temperature heating water application has been in meeting comfort heating loads using energy with a low thermal potential. Comfort heating requires supply temperatures above the desired space temperature in order to satisfy the load. This can become difficult to achieve when the source energy is not at a temperature significantly above the required space temperature. Either the temperature differentials associated with the heat transfer process make the energy delivered to the supply stream virtually useless for meeting the heating needs of the space, or the needs can be met, but they are met with high air flow rates at relatively cool temperatures, both of which cause other comfort problems.

The most obvious solution to this dilemma is to use a heat pump to improve the thermal potential of the recovered or renewable energy. But this has the disadvantage of adding complexity, cost, and the need for a conventional energy input to operate the heat pump to the process. These factors can be sufficient cause to abandon the approach.

In many cases, radiant slabs represent an ideal way to address comfort heating loads using low-grade thermal energy. Radiant slab heating is not a particularly new technology. The approach has been used for 50 years or more. But, until recently, the systems were constructed by embedding copper, steel or iron piping in the slab when it was poured. The thought of inadvertently introducing a leak into the system during the concrete pour that

---

[3] Domestic water loads require leaving temperatures higher than this, but the low temperature water system can eliminate a significant portion of the domestic water burden by providing preheat.

would go undetected until after the concrete had set gave many contractors and engineers some sleepless nights. In addition, corrosion and leaky joints frequently resulted in the failure of these circuits and the repairs were difficult and costly due to the problems associated with locating the leak and then opening up the slab and repairing it.

New thermoplastic materials address concerns about corrosion via immunity to it. Concerns about fitting leaks are mitigated because the material provides the capability to fabricate complete circuits with no joints. The concerns about introducing problems during installation are still valid, but a good quality control process generally will ensure a problem free installation.[4]

Current Applications

In addition to the MHC system, which will be discussed in detail in the following case study, the low temperature hot water concept has been used or is being considered on the following systems.

- In a surgery addition project at a Midwestern Hospital, a small water cooled chiller was installed to provide 40-42°F chilled water for the surgery air handling units with out needing to operate the entire central plant at that temperature (normal operating temperature range of 45-47°F). In addition to saving energy in terms of chilled water plant efficiency, the condenser water from the chiller was used to serve the suites reheat and preheat loads at standard condenser water temperatures.
- In another Midwestern Hospital expansion project condenser water from one of the multiple networked chilled water plants on the site was used to provide reheat and preheat for surgery, laboratory, and patient care areas.
- A Northwest office facility equipped with radiant slab heating systems in some areas is considering operating its chiller as a heat pump to recover energy from the air handling systems and reject it for use in the radiant slabs and reheat at or below 95°F. Recent changes in the utility rates in the area make this approach economically viable if the first costs of the necessary heat transfer equipment and piping modifications are not excessive.
- A Northwest semiconductor facility has taken a first look at recovering heat from their chiller plant for use in preheat and reheat applications for both HVAC and ultra-pure water (RODI). While much additional work needs to be done to determine the true economic viability on this existing plant, the investigation thus far has indicated that, it may be an option worthy of consideration as a retrofit once the semiconductor market has turned around.
- A Northwest high rise office building is contemplating recovering heat from the condenser water system to serve reheat, preheat and space heating loads. The building has low temperature air systems that will require chiller plant operation into the low to mid 40°F outdoor air temperature range. The proposed system will allow recovered energy to serve the summer time and swing season reheat loads associated with the ventilation needs of the building. In addition, a significant portion of the perimeter

---

[4] Pressurizing the lines during the pour and then monitoring the pressures, couple with a pre-agreed upon plan of action in the event of a problem provides a method to quickly identify, isolate and correct a problem when it occurs and before the concrete sets.

heating load will be served by radiant slabs. Since there are over 4,000 hours per year between 40 and 60°F at the office building location, the radiant slabs offer a very viable way to serve the space heating load using energy recovered from the internal gains in the building via the chilled water plant. (The central plant portion of this system is depicted in Figure 1.)

The Evolution of a System - A Case Study

In the following section, the low temperature hot water system at the Memorial Hospital of Carbondale (MHC) is discussed in detail. MHC is a facility where one of the authors is the Director of Facilities and the other was an engineering consultant when the system under discussion was installed. The final system configuration at MHC was the direct and indirect result of a planning and installation process that took nearly 15 years to be fully realized

Birth of an Idea

The concept evolved during design development for a project that replaced the existing 100% outdoor air unit serving the Labor and Delivery Room (LDR) at MHC with a new custom unit. The project also made significant modifications to the system served by the air-handling unit and was part of an energy conservation and ME system upgrade master plan. In the course of reviewing the coil selection, the project's principal engineer pointed out that a deeper coil might meet the long term needs of the project better than the 2 row coil that was currently selected. (1980, McClure). He based this observation on his belief that the current 200°F supply water temperature used by the existing system was probably higher than was required given the loads that were served. In addition, he pointed out that the coil would need to be connected as a pumped secondary circuit to protect it from freezing due to the preheat function that it provided. Thus the entering water temperature to the finned elements would be reduced below the system supply temperature and the coil would need to be sized based on this mixed temperature and thus would be deeper, probably 4 to 6 rows vs. the two currently anticipated.[5] Finally, he pointed out that this added coil depth was a good long term planning strategy because it paved the way for the coil to be served by recovered energy or renewable energy at some point in the future.

As a result, the unit was selected with a 6 row heating coil instead of the 2 row coil initially targeted based on the 200°F supply water temperature. This approach was also used for subsequent preheat coil selections made for other projects at the Hospital, paving the way for the system configuration that exists today.

---

[5] A pump secondary arrangement would provide the necessary protection from freeze-up by circulating water continuously through the coil at a high flow rate. But, this high flow rate would exceed the required supply flow rate at 200°F, thus, mixing of the coil's return water with the supply from the central system would occur in the secondary circuit and the supply temperature to the coil heat transfer surfaces would be below the supply water temperature. The pressure losses associated with the additional depth could be managed by keeping the face velocities low and the fin spacing modest. Since the unit to be purchased was going to be of high quality, it would most likely be in place for many years. Since it operated 24 hours per day, the lower face velocities would translate into lower pressure drops through all of the unit's components and thus lower operating costs. In many cases, these lower operating costs justify added first cost to purchase air-handling equipment cross sectional area (ASHRAE).

The Next Step - Installation of a Heat Pump

In 1984, the local utility began offering a rate schedule that made the purchase of electricity during non-peak hours very economical. Even without this incentive, the operating economics of the heat pump were marginally favorable given the existing plant's operating characteristics. Reheat and domestic hot water loads were a significant portion of the energy use at the facility. These loads could not be eliminated due to the nature of the health care processes in the facility and the licensing requirements associated with them. Since the Hospital was in a rather warm and humid climate, there were often significant cooling and dehumidification loads that occurred simultaneously with the reheat and domestic hot water loads any time the outdoor air temperatures were above 50°F.

Via experimentation, the operating staff had discovered that they could easily meet the reheat and comfort heating requirements of a significant portion of the facility using supply water temperatures in the 120-180°F range, with the warmer temperatures required only during extreme winter weather.

An engineering analysis of these factors lead to the conclusion that the Hospital should install a heat pump that generated chilled water and rejected the heat in the 130-140°F range to serve the reheat loads and domestic water loads. The heat pump was installed as a component of the heating hot water system in the primary boiler plant and included thermal storage capabilities[6] and a plate and frame heat exchanger to provide domestic water preheat. The location allowed it to immediately serve a significant portion of the domestic water and reheat loads, since they were concentrated in the portion of the facility. And it set the stage for allowing it to serve the rest of the facility when all of the independent hot water systems were integrated into one central system under a future phase of the master plan.

Achieving the Current Configuration and Low Temperature Energy Recovery

The final step in achieving the current system configuration began with the authors and Joe Cook, the Hospital's maintenance foreman, standing in the central plant one July day and contemplating a project that was about to start. The topic of discussion had moved to how low the heating water supply temperature could be in the summer time. It had just dawned on the project engineer that it might be possible for a one row reheat coil to deliver neutral or near neutral air when supplied with water in the 85-95°F range.[7] If the system could operate at that low of a supply temperature, then it seemed possible that the reheat

---

[6] The thermal storage tanks provided a thermal flywheel that allowed the heat pump to operate at peak efficiency when it ran. They also allowed the heat pump to serve on-peak loads using energy it consumed during off-peak hours, further improving its economic attractiveness.

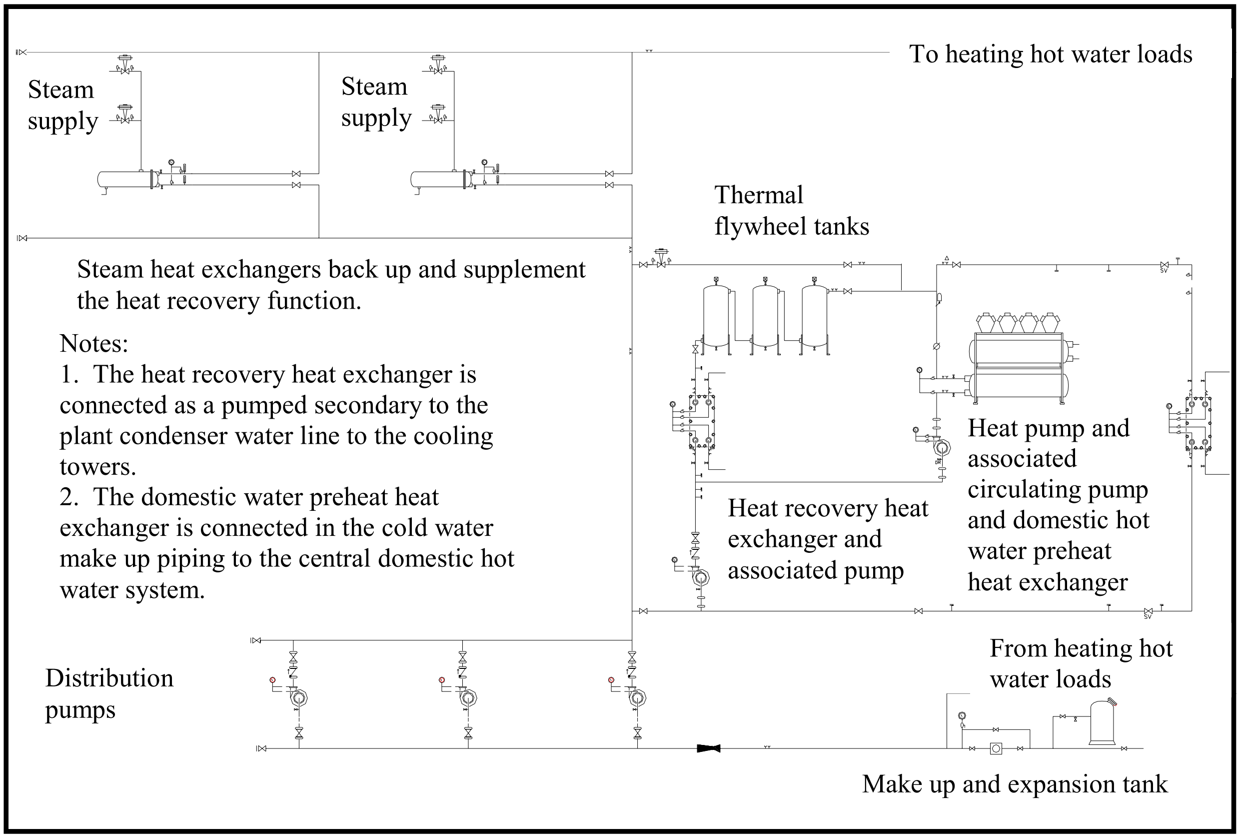
[7] For a reheat coil serving a space with a net cooling requirement like an internal zone or a perimeter zone during warm weather, the warmest air that will ever be required leaving the coil is air at the same temperature as the space. In fact, air will only be required at this temperature if there is absolutely no load in the space; no solar or envelope gains, no lights, no occupants, no operating equipment of any kind. The only time a reheat coil will need to deliver air to the space that is warmer than the desired set point is to warm it up or to make up for energy losses from the space, conditions generally associated with a perimeter zone during cold weather. Existing coils that have design conditions which required relatively hot supply water temperatures to deliver hot air to offset heating requirements can actually serve the loads that exist during the summer or at internal zones using water at much lower temperatures.

requirements could be satisfied via heat recovery directly from the condenser water system. At this point, two things happened.

- The authors, being engineers, engaged in a discussion of the pro's, con's, technical merits, limitations, and practicality of modeling all of the existing reheat coils on the site to determine their performance characteristics with 85-95°F supply water.
- Joe, accustomed operating in the real world, said "lets see when we get a cold complaint" and walked over to the hot water system temperature controller and turned it down 5°F, a process he repeated periodically for the next several days.

Joe's science experiment quickly revealed that the existing system could be expected provide a comfortable environment during the non-heating season with water temperatures in the high 80 to low 90°F range if one or two reheat coils were replaced. On this basis, the project incorporated heat recovery from the condenser water system into the design of the integrated heating water systems. The resulting configuration, shown in Figure 2, includes several important features.

Figure 2 - Final System Configuration at Memorial Hospital of Carbondale



Steam heat exchangers back up and supplement the heat recovery function.

Notes:
1. The heat recovery heat exchanger is connected as a pumped secondary to the plant condenser water line to the cooling towers.
2. The domestic water preheat heat exchanger is connected in the cold water make up piping to the central domestic hot water system.

Source: PECI, McClure Engineering, 2002

- Hospital codes required 100% back-up capability for the heating plant. The consulting firm's design philosophy included providing a proven "back-door" for systems that were based on less proven, more exotic approaches to engineering problems. These requirements and the existing equipment complemented each other and resulted in a system that, while complex in its most sophisticated operating mode, failed to a fairly easily operated variable flow heating water system served by steam heat exchangers. The existing heat exchangers also provided trimming capacity for times when the recovered energy did not meet the operating loads.

- Heat recovery capabilities from the condenser water system via a new plate and frame heat exchanger were accommodated by the design.8 The control system was arranged to optimize the supply temperature set point to use the recovered condenser energy when it was available due to concurrent requirements for water cooled mechanical cooling. Typically, this occurred when outdoor temperatures were above approximately 65°F. An air cooled chiller provided chilled water between 50 and 65°F outdoors. Below 50°F, all cooling requirements were met by economizer cycles or the 100% outdoor air configuration of many of the systems.
- Heat recovery capabilities from chilled water system via the existing heat pump were retained and utilized during the winter months where the low, off peak electric rates often made operating the heat pump economically attractive as compared to the boilers. In this mode, the Hospital's automation system was used to load the chilled water system only to the point required to offset the heating requirements. This was accomplished by over-riding the economizer cycle on a large, nominal 40,000 cfm air handling unit and raising the mixed air set point as necessary to create a load on the chilled water coil.

The Owner's Perspective

From the Owner's perspective, low temperature hot water systems can offer significant advantages. Figure 3 is a graph of the gross energy consumption for MHC over a period of years. Building square footage is also shown. There are several very interesting things to be noted.

- The building square footage has increased by 94%, but the current building energy consumption in terms of Btus has only increased by 17% over the baseline in 1979 when the first energy audit was done and the ongoing energy conservation and ME systems improvement program was initiated.
- The typical Illinois Hospital spends about \$.80 per square foot on gas and \$1.55 per square foot on electricity for a total energy cost of \$2.35 per square foot (Grumman/Butkus Associates). MHC spends \$.39 per square foot for gas and \$1.49 per square foot for electricity for a total of \$1.88 per square foot.

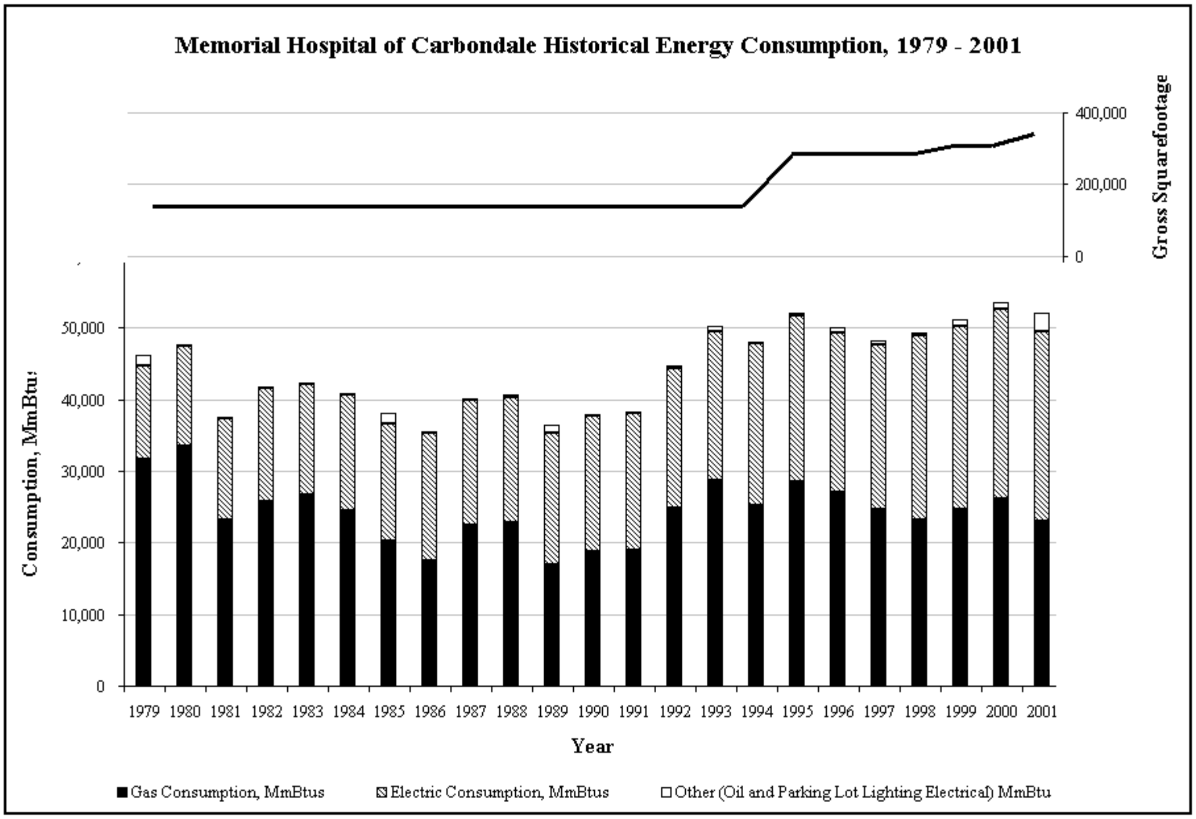
Certainly, the low temperature hot water system and the associated energy recovery equipment have contributed to the Hospital's lower than average energy usage pattern. But there are other significant contributing factors. The process has been supported by a commitment from management to install systems that provide high quality, reliability, flexibility and efficiency. This commitment was matched with long term planning and budgets that supported these concepts, both for new construction as well as independent ME

---

[8] In an emergency, the plate and frame heat exchanger also allows the heat pump to reject heat to the cooling tower so it can serve as a back-up chiller if one of the primary chillers were to fail.

projects targeted at improving the existing infrastructure. Management understands the "bottom-line" savings and long term cost avoidance that result from energy conservation and efficient operation at the facility. In addition, the system redundancy that resulted from the long range planning and implementation of various energy conservation projects has resulted in little if any down-time of the building's systems over the years. Patient care and operations have continued without interruption, which is critical in a health care environment.

Figure 3 - MHC Historical Energy Consumption and Building Gross Square Footage



Source: Memorial Hospital of Carbondale, PECI, 2002

The quality of the facilities group charged with operating the systems has also been a significant factor in the over-all success of the ongoing energy conservation efforts. All members of the team have an interest and perhaps even a passion about operating and maintaining the facility in a professional and efficient manner. Management has supported this commitment by endeavoring to provide them with the training, equipment and systems they need to operate the physical plant to its fullest potential. This includes significant investments in building automation technology and related training to allow the more sophisticated control sequences required by the low temperature heating water system and other systems to operate seamlessly and efficiently.

Interaction with the architectural and engineering design teams has also been supported and encouraged. The facility maintenance staff looks for answers and solutions to any noted operating deficiency and feel free to contact the design engineers for consultations as needed to ensure the systems operate as designed. This synergy with the design team is a two-way street that has helped to ensure that the people charged with operating the systems are fully aware of the intent of the designers. Going the other way, it has provided ongoing feedback regarding the real-world performance of the designer's systems that is invaluable in making better design decisions on future projects.

A significant enabling factor for the interactions between the operating staff and the design team is the Hospital management and administration's commitment to long term relationships with the designers rather than procuring the services of a design team on an as needed basis based on competitive bidding or an RFQ/RFP process. This approach ensures that the design team is intimately familiar with the systems, structure, programs and operating philosophy of the Hospital. This intimate knowledge is mutually beneficial to the designers and the Hospital and gives the design team a sense of ownership, responsibility and pride that is difficult to achieve when projects are worked on in a piece-meal basis.

Conclusion

The low temperature water systems and concepts discussed in this paper are proven technologies that have been successfully applied to real world operating environments. While all of the installed applications know to the authors to date have been for health care and laboratory facilities, the potential exists for very beneficial use of this approach in other areas including clean rooms and office environments as illustrated by some of the project cited previously. If properly applied, the low temperature recovery and distribution concepts presented here-in will go a long way towards making energy intensive HVAC processes more sustainable. As an added benefit, the operating costs of the systems that use these concepts will be markedly lower than similar applications using more conventional approaches.

Acknowledgements

The authors wish to gratefully acknowledge the assistance of Linda Irvine, a project manager at PECI for her assistance in copy editing this paper for final publication. They also wish to thank McClure Engineering Associates Inc. and the staff in the Memorial Hospital Facilities group for their time and assistance in gathering the case study information.

References

Rumsey, Peter, and Lotspeich, Chris February 2002. "Reinventing HVAC Design*."* in *Environmental Design and Construction.* San Francisco, CA.: Business News Publishing Company

McClure, Charles J.R. (C.J.R. McClure and Associates Inc.) 1980, Personal conversation

ASHRAE Energy Professional Development Series. *Air System Design and Retrofit for Energy/Cost Effectiveness*. Atlanta, GA; American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE 2001 Handbook of Fundamentals. *Chapter 25 - Thermal and Water Vapor Transmission Data*. Table 11A, page 25.20. Atlanta, GA; American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Grumman/Butkus Associates, Energy Consultants and Design Engineers, Evanston, Illinois