Two-Pipe HVAC Makes a Comeback: An Idea Discarded Decades Ago May Be the Future of School Heating and Cooling

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ABSTRACT

A 2-pipe HVAC system is one that uses the same piping alternately for hot water heating and chilled water cooling, as opposed to a 4-pipe system that uses separate lines for hot and chilled water. Two-pipe originated 50 or 60 years ago as a cost-effective way to add air conditioning. The premise was a seasonal change-over, where buildings were heated from fall to spring and cooled from spring to fall. Clearly, it saved money not to have to install a second set of pipes, but operationally, the idea never really worked in the cool morning – warm afternoon typical of a spring or fall day.

In 1993, the primary author, a consulting engineer, was asked by a representative of the New Albany, In. school district to design air conditioning for a school on an impossibly small budget. The engineer's answer reflected conventional wisdom: "the only thing you can afford is 2-pipe, but everybody knows that won't work." Nonetheless, the engineer revisited the old system in light of modern technology. The result solved the workability issues and maximized the inherent economy of 2-pipe without compromising indoor air quality, occupant comfort, or humidity control. The result was a remarkable efficient modern 2-pipe system that is proving to be less expensive to build, less expensive to operate, and easier to maintain than any other option for heating and cooling buildings. To date, the new 2-pipe concept has been engineered into 120 buildings. In almost all cases, the resulting utility bills, with air conditioning, have been significantly less than the pre-2-pipe bills without air conditioning.

Introduction

A few decades ago, two-pipe fell out of favor because it took too long to switch from cooling to heating and back again. The switching over process was complicated and wasted energy as well as maintenance personnel time. Further, during spring and fall, many buildings require heating in the morning, cooling in the afternoon, and heating again in the evening. Old-style two-pipe systems simply could not cope with such operational demands. Accordingly, four-pipe system--a pair for the supply and return of hot water and a pair for the supply and return of cold--have held sway for several decades. However, there's a resurgence of interest in two pipe HVAC due to some innovative system designs that have overcome past shortcomings. It's done through a combination of clever mechanical design, modern digital sensing and controlling equipment, high-efficiency boilers and chillers, and attention to "whole building" conservation opportunities.

Retrofit School Work

In thinking through how to design a satisfactory two-pipe system, it was decided right away that the old way of changing over from heating to cooling in the spring and back again in the fall would leave a lot of people unhappy. Accordingly, along with keeping costs low, the ability to change over daily became a major design objective. Thus, the key questions that needed to be answered in the design process to make two-pipe changeover viable were:

- How quickly can changeover be accomplished? The old systems would take about a day of constant operator attention.
- How complicated must the resulting system be? The old systems had multiple valves, pumps, drains, etc.
- When (as a function of room temperatures and weather) should the change-of-modes process be initiated? The old systems changed over once a season.

As the initial two-pipe design evolved, addressing these design issues developed as follows:

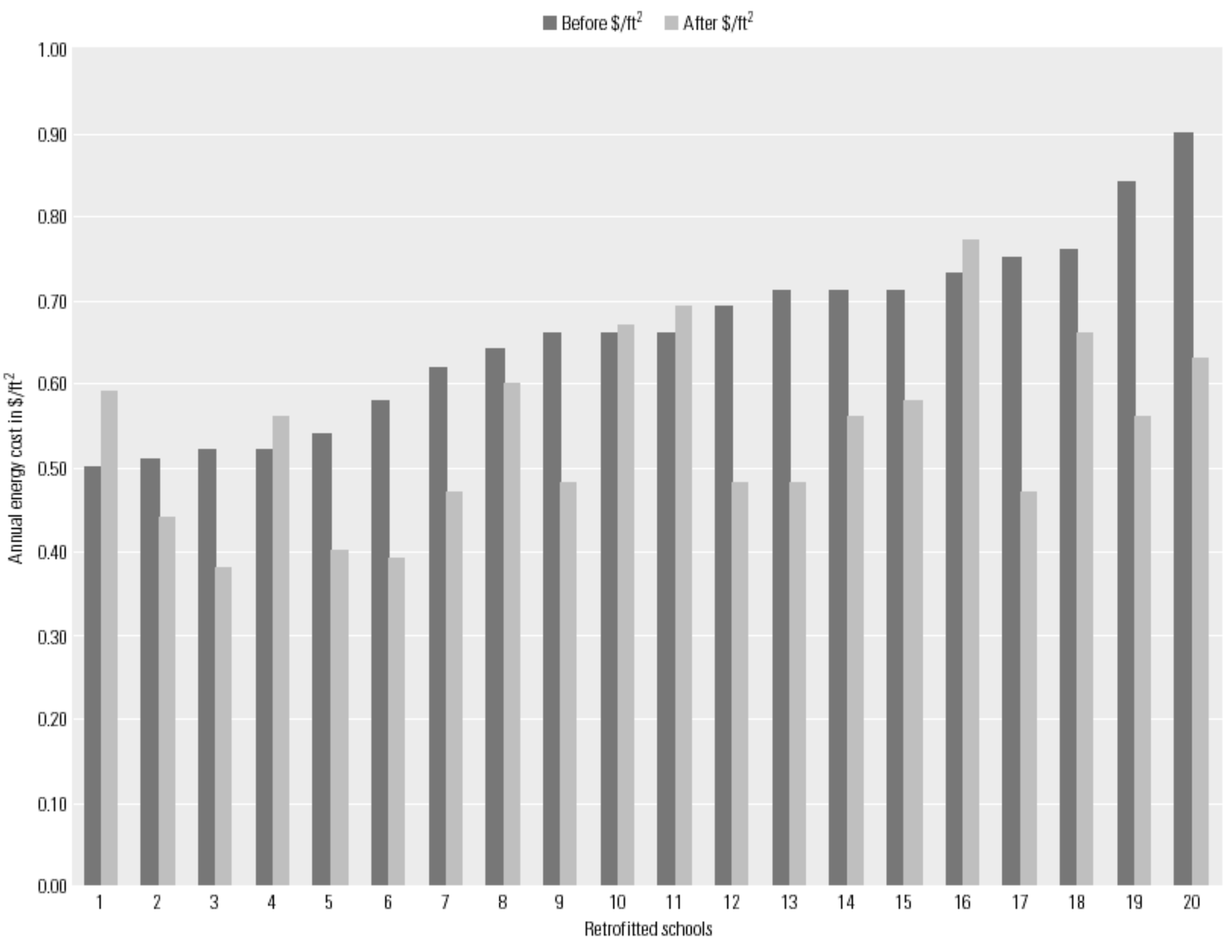
(1) Changeover can be accomplished with very little loss of energy in 20 minutes with no human intervention whatever.
(2) The system is remarkably simple from the mechanical point of view so that a single valve controlled by a microprocessor switches from heating to cooling and back again. Genuine complexity is in the software which is nonetheless simple from the user's point of view; and
(3) The change from morning heating to afternoon cooling should be initiated when the outside air temperature is rising above 60 F and all of the zones are comfortably warm (all local thermostats are satisfied).

Evansville-Vanderburgh School District Retrofit

Initial success with the New Albany, Indiana school district mentioned in the abstract led to other opportunities, the largest of which was the Evansville-Vanderburgh School Corporation in southern Indiana. The school district has 35 school buildings, twenty of which were not air-conditioned. This lack of cooling was identified as a major shortcoming of the educational environment in this southern Indiana climate whose weather routinely includes uncomfortably high temperatures and humidity.

All 20 schools had air conditioning installed for the first time and each also had lighting retrofits. As shown in Figure 1, the before-retrofit cost per square foot for energy ranged from \$0.51 to \$0.90 and averaged \$0.66. After-retrofit cost per square foot for energy ranged from \$0.38 to \$0.77 and averaged \$0.54, an overall savings of \$0.12 per square foot for all 20 schools, or 18.2 percent. Fifteen of the 20 schools retrofitted experienced first year savings, the best of which was \$0.28 per square foot.

Figure 1. Energy Savings in Evansville Schools



Source: Engineered Systems

In year three of the retrofit, the 20 buildings in the project saved 3,780 megawatt hours of electricity or $429,214. Year three natural gas savings were 1,011,066 therms or $441,780, for a total annual dollar savings to the school district of $871,000.

How It Is Done

Four pipe systems were designed to overcome the shortcomings presumed inherent in two pipe systems. Designing around those shortcomings required some innovative engineering. "Seek simplicity—but distrust it," an aphorism from the philosopher and mathematician Alfred North Whitehead, could be taken as the first principle of modern 2-pipe design. ASHRAE volumes of the 1970s and 1980s included many pages on two-pipe designs, but they were hopelessly complicated. The systems had primary and secondary pumping, many valves to control flow and isolate parts of the system, and a number of expansion tanks. All of this was eliminated for cost savings, ease of operation, and simplicity. The result is a system that requires only one valve to change from heating to cooling. There are no blending valves, no secondary pumps, and no extra expansion tanks.

A schematic of a generic system is shown in Figure 2. The three-way valve immediately above the chiller at the bottom of the diagram switches the system's mode of operation. In the heating mode, the return line from the room terminal units (typically fan coils or unit ventilators) bypasses the chiller and goes to a header that feeds the boilers. When the main three-way valve is moved to the cooling position, return water is directed through the chiller. The "heat trap" where the boiler and chiller outlets converge, is an example of the design ingenuity. ASHRAE handbooks show anywhere from two to six motorized change-over valves. The heat trap allows this design to use only one valve and nature – the differential densities of hot and cold water – to isolate the boiler and chiller circuits with no moving parts and no added cost.

As shown in Figure 3, the motor-driven changeover valve is automatically actuated by a command from the operating software whose control algorithms account for outdoor temperature, temperatures in every zone of the system, time of day, and day of the week.

The heat trap is shown in Figure 4. When there is no flow in the heating loop, the water at the top of the heat trap is hotter (less dense) than the water at the bottom of the loop. Accordingly, higher density cold water from the chiller will not come through the heat trap, thereby protecting the boilers.

By keeping things as simple as possible, valves are minimized, so the resistance to flow through the system is low. As a result, pumping power can be quite low as well. Keeping pumping power low saves on both front end costs and overall energy costs. It's routine for pumps for HVAC systems to account for five percent or even more of total HVAC system energy. A properly designed two-pipe system will use half that. Since the coils and piping are sized for the larger flows required for cooling, when the system switches to heating (about 75% of the operating hours), pump laws dictate that delivering two thirds the flow only takes 30% of the pump power. Of course, high efficiency motors are used (Figure 5). This two-motor strategy also facilitates maintenance, as the idle pump is always available as a stand-by.

Figure 2. Two-Pipe System Diagram

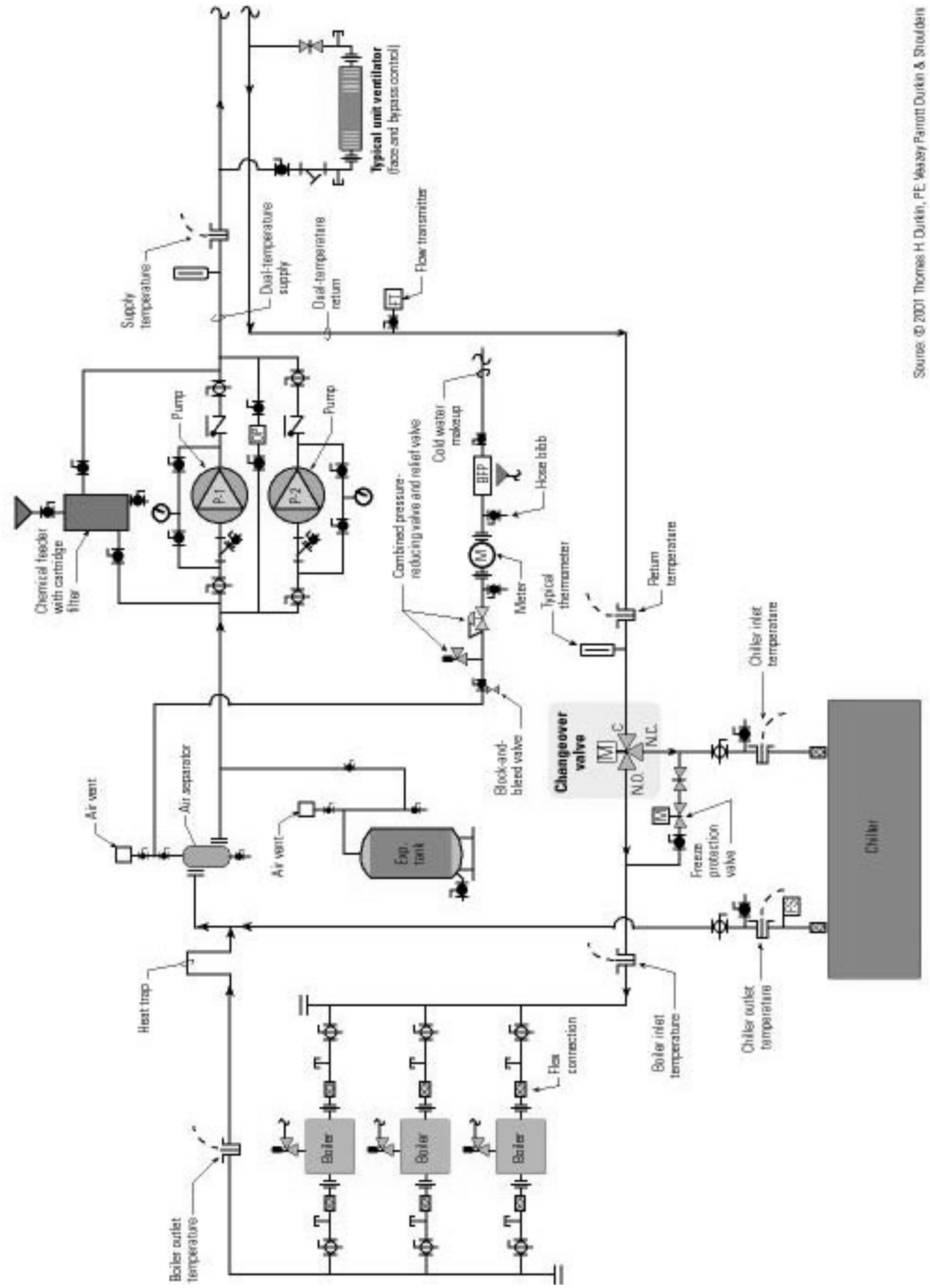
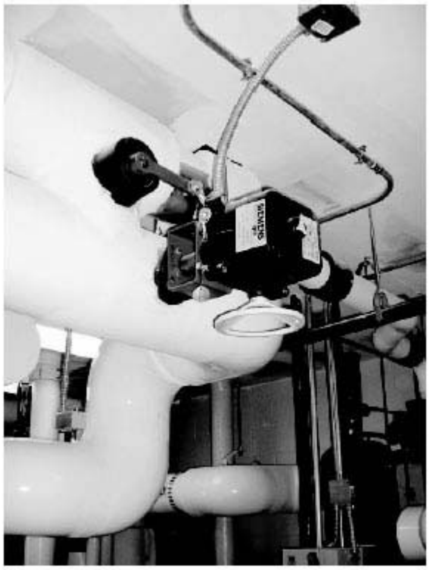


Figure 3. Changeover Valve **Figure 4. Heat Trap**



Source: Jeff Bowers photo, Veazey, Parrott, Durkin & Shoulders

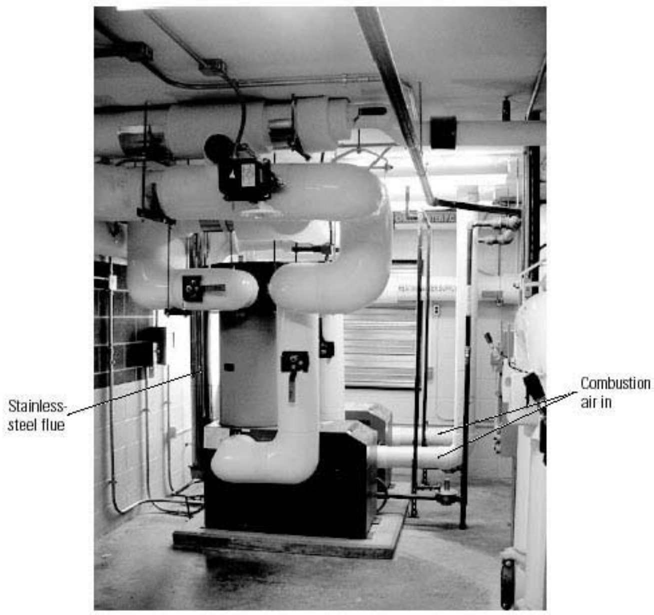
Figure 5. Circulation Pumps at a 50,000 SF Elementary School. The Big Pump (10 Hp.) is for Cooling, the Little Pump (3 Hp.) is for Heating.

Source: Greg Stephens photo, Veazey, Parrott, Durkin & Shoulders

Efficient boilers. Another ingredient that makes the new two-pipe approach especially efficient is the use of low mass condensing boilers with thermal efficiencies of 96%, versus 80-82% for conventional boilers. The real operational savings are proving to be much more that the incremental difference between 80 and 96%. By carefully designing the piping, boiler start-up losses can be eliminated, and by designing the balance of the heating system for low temperature water, parasitic piping losses can be eliminated. A 2-pipe boiler plant operates at 130F on the coldest day of the year, compared to 180 or 200F for conventional boilers. The 130F is significant because it means that the heat of condensation of the water vapor in the flue gasses is recouped continually. Conventional boilers must operate at considerably higher temperatures since their metallurgy cannot tolerate temperatures that low. Some steam-to-hydronic 2-pipe conversions have resulted in a gas savings in the 70% range, and 180F hot water-to-2-pipe conversions have generated savings in the 40-50% range. (Imagine the energy implications on a national basis if all of our public buildings were being heated with one half or one third of the energy. Imagine the national impact on ozone levels and green house gasses.)

The pair of million Btu per hour condensing boilers shown in Figure 6 can be throttled down to 67,000 Btu per hour (16 to 1 turndown). Combustion air is introduced through the PVC pipes on the right. The stainless steel flue pipe on the left is never so hot that it would burn a hand.

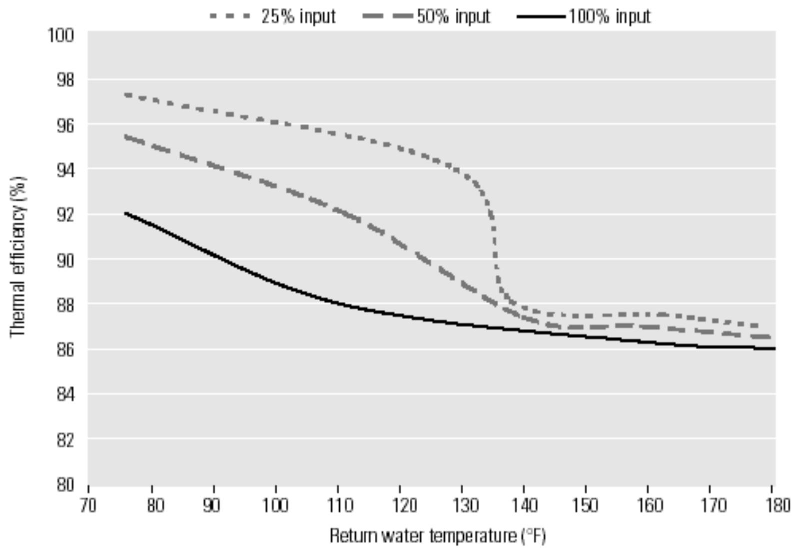
Figure 6. Pair of Condensing AERCO Boilers



Source: Greg Stephens photo, Veazey, Parrott, Durkin & Shoulders

As shown in Figure 7, efficiencies at part load exceed full load efficiencies, the inverse of the case with most other boilers. Note that lower return water temperatures also result in higher efficiency. When throttled back to 25 percent of full load input and with a return water temperature of 110 F, this boiler achieves 96 percent efficiency.

Figure 7. Efficiency Curves for the Benchmark 2.0 AERCO Boiler



Source: AERCO

Delivery

In 1917, Herman Nelson invented the first unit ventilator. It consisted in little more than a hole in the wall, a steam radiator, and a fan, but heated fresh air was successfully brought into a conditioned space. Modern versions of unit ventilators in each classroom of a school are key elements in modern two pipe system designs. They regulate temperature, ventilation rates, and (to a degree) humidity. Instead of inserting valves to regulate flow from the boiler or chiller through the heat exchangers in the ventilator, the flow of water is constant—and the pressure drops in the system are low. Temperature is controlled by varying the volume of air that flows across the heat exchanger by manipulating dampers in each unit ventilator. A second damper regulates the volume of outside air introduced into the air stream. Accordingly, with this "face and bypass" damper system, air introduced into a conditioned space is a combination of return and fresh air, some portion of which (from 0 to 100 percent, depending on the difference in the thermostatic setting and instantaneous room temperature) passes through the "coil," a water-to-air heat exchanger. Additionally, the fan speed in the unit ventilators can be controlled step wise: low, medium, and high. See Figure 8.

Unit Ventilators with Face and Bypass Controls

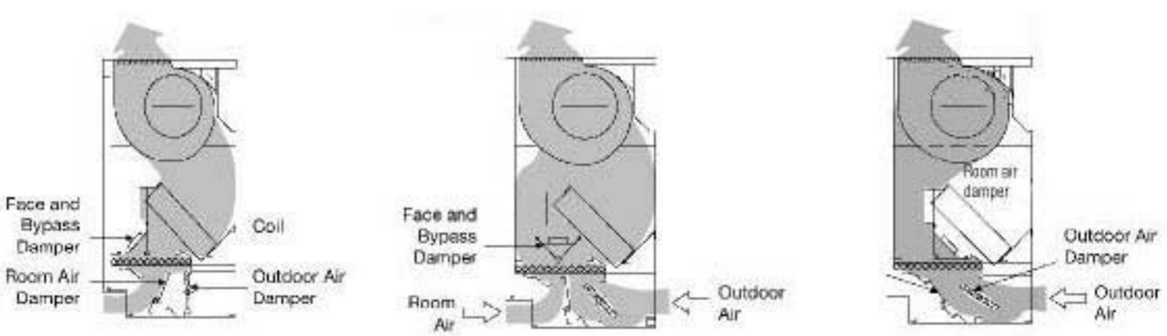
Face and bypass damper systems in unit ventilators have a number of advantages over unit ventilators that regulate space conditioning energy using valve control By their nature, control valves introduce resistance to flow which is ultimately reflected in a higher total pressure head the pumping motors much overcome. So motors must be larger and electricity consumption is higher. More serious, valve control units are at risk of freezing under winter conditions when ventilation air is brought in during periods when the thermostat is satisfied. Designs to avoid the problem exist, but they add costs and complications that risk maintenance problems.

Figure 8. Unit Ventilator with Face and Bypass Controls

Source: Jeff Bowers photos, Veazey, Parrott, Durkin & Shoulders

With a valve control unit, the control valve regulates the flow of warm water (in the winter) or chilled water (in the summer) to the heat exchanger while all of the outside and return air is pulled through the heat exchanger at a volume that depends on the fan speed. With the face and bypass system shown in Figure 9, the flow of water through the heat exchanger is constant, but the amount of return and outside air that passes through the heat exchanger is varied with the bypass damper.

Figure 9. Unit Ventilators with Face and Bypass Control



Source: Veazey, Parrott, Durkin & Shoulders, AAF Herman Nelson

Dealing with humidity. Indoor air quality and humidity control are two frequently cited reasons why 2-pipe fell out of favor. On high humidity days in the cooling season, it is virtually impossible to both maintain ventilation rates at 15 cfm per occupant and humidity levels below 60 percent, both mandates of ASHRAE Standard 62*, Ventilation for Acceptable Indoor Air Quality*. Yet through careful manipulation of face and bypass dampers and modulation of fan speed, ventilation requirements can be met while keeping humidity levels in check. The real trick is to maintain the coil (heat exchanger) well below dewpoint and direct all of the outside air through the coil. The return air is already conditioned, so much of that can be bypassed around the coil on its way through the fan and into the classroom. Running chilled water at full volume through the coil aids the dehumidification function, whereas modulating its volume makes it less effective.

This was a key point shown in a recent article in Heating/Piping/AirConditioning, where comparisons are made in the performance of unit ventilators using (1) a valve control system, and (2) a face and bypass controlled system (Durkin 1999). These were the conditions assumed for the analysis:

- Unit ventilator with a 1200 cfm fan
- 4.5 tons (54,000 Btu/hr) of cooling load
- 450 cfm outside air (15 cfm per person for 30 occupants)
- 75 degree room temperature.
- Outside air 95 F dry bulb, 78 F wet bulb (48% relative humidity)

Under this very typical circumstance, the valve control system worked adequately at full load, but was unable to maintain part load relative humidity below the 60%RH code limit (this one part load example was 68%). Whereas the face and bypass system maintains 56% RH.

Controls

Energy Management Systems (EMS) are integrated into each new two pipe HVAC designs. In fact, digital technology is a necessary condition for these systems to work. Twenty years ago, the technology did not exist to allow for controlling equipment in the boiler room and local environments well enough to ensure comfort and efficiency, let alone switching over modes without any human intervention All that has changed.

Now, each installation has electronic equipment installed that allows for supervising temperatures, set points, flow rates, equipment status, and the like from computers installed at each installation or remotely. The facilities personnel can monitor every sensor in every school in a school district from the convenience of his office. The software provides an electronic plan view of each school, shows readouts of sensors, and signals variations from setpoints when readings are beyond a specified tolerance. Since local building personnel can monitor the data on their schools at the same time, this facilitates the informed discussions and expeditious resolution of problems.

Buildings are set up to require a minimum of human interventions during routine operations. The EMS has calendar information stored so that temperatures and ventilation rates are varied to meet occupancy requirements or, during unoccupied periods, to minimize energy consumption. Supply temperatures from boilers and chillers are varied to maximize efficiency as a function of outdoor dry bulb and wet bulb temperatures as well as circumstances of occupancy. In the case of classrooms in schools, teachers have thermostats they can control to ensure local comfort, but typically, the range of options covers only six degrees F.

Special Case Retrofit

Most institutional buildings retrofitted for energy efficiency and air conditioning already have a pair of pipes that run from the boiler room to local zones. Although these are usually replaced, the new insulated piping can routinely be routed through chaseways made for the old piping, so major surgery is avoided. Of course, this is another reason two pipe systems are less expensive to install in retrofit jobs than are four pipe systems; the jackhammer bill is lower. However Public School Number 93 in Indianapolis presented special difficulties--it was an all electric building without air conditioning. Accordingly, it had neither dedicated chaseways for piping nor a boiler room. Although its brick construction has resisted the wear of a half a century of Indianapolis winters, its poorly-insulated walls coupled with electric resistance heating made for large heating bills. Rather than building a new room for the boilers, a janitor's closet now houses a pair of million Btu/hour condensing boilers, circulation pumps, water treatment equipment, control electronics, and sundry plumbing. (The small foot print of a 2-pipe boiler room is another first cost saving feature). Energy cost savings from converting this building from electric resistance heating to a two-pipe HVAC system that includes cooling are not quite as impressive as some other schools, primarily because the old system was bringing in virtually no fresh air.

Two Pipe Operators' Group

The hundred-twentieth two-pipe job was designed in the spring of 2002, so there's a growing number of maintenance people who are gaining practical wisdom in operating two-pipe systems. The process of sharing this wisdom, training new people, and dealing with questions as they arise is enhanced by a unique organization called the "T-POG"—the Two-Pipe Operators' Group. As often as not, those who operate and maintain energy systems in schools don't have much formal education in HVAC theory or practice. Accordingly, it's especially useful to get people together to talk about how systems are supposed to work, tell them about new technologies in the offing, and help them deal with problems that crop up. The idea has taken hold and T-POG members are proud of their special status. They have a web site (www.vpdsweb.com/vpdseng/) that prominently displays the group's motto: "None of us are as smart as all of us." The T-POG group has a major event every six months. It's a full-day meeting where workshops are offered on a variety of topics relevant to the care and feeding of two pipe HVAC systems. A variety of new products and ideas are also introduced at these meetings. A camaraderie has built up among group members, who are fond of pointing out the features of the two-pipe systems they operate that make them outperform the systems operated by colleagues. Such friendly competition is to the benefit of all.

New Construction

Most two-pipe work undertaken to date has involved retrofitting existing buildings, typically institutional structures. Although retrofitting work often demands more creativity than does new building design work, is a similar approach to new construction likely to be as successful? In the case of schools, the answer is clearly yes. The key reason is that there is a tradition of unit ventilators in 900 square foot classrooms which function very effectively in an economizer mode (access to outside air for free cooling, since schools are generally heat positive down to about 35F outside air temperature). Running energy in the form of water in a closed loop from a chiller or a boiler to the zones where it is needed has a number of advantages. The horsepower to deliver the energy is many times less than is necessary with air ducted systems, which require a good deal of fan power even with variable air volume designs. Pipes take up much less space than ducts, and the extra volume can make a substantial difference in controlling building cost. The principal author's firm has functioned as the design/builder for two new buildings in which they have installed two pipe HVAC systems, both middle schools of about 90,000 square feet. Savings in first costs due to going with two-pipe was from $400,000 to $500,000 for each of these new buildings, whose total cost for construction was about $9 million. Energy savings are on the order of 15 cents per square foot per year. Of course, in some modern buildings, there is a need for simultaneously cooling in some places and heating in others. This can be controlled to a large extent with overhangs and specularly selective glazings for sun control, plus air sealing and adequate insulation. However, when certain areas with a concentration of computers or office machinery require cooling for much of the year, it may be necessary to use a separate small four-pipe system or simply a small dedicated chiller. The trick is to accommodate special cases when they arise, while maintaining a high level of energy efficiency consistent with intelligent controls and overall simplicity of design. In all buildings examined so far, the two-pipe system approach works quite well for most zones throughout the year.

Sources of Efficiency

- Condensing boilers - operating 100% of the time in the condensing mode. Schematic arrangement of boilers eliminates start-up or stand-by losses. Space temperature feedback for supply water reset, both up and down.
- Aggressive scheduling – only operate the system when the building is occupied, and only operate the portions of the building that are occupied.
- Managing outside air – use "normal" and "event" modes for large assembly spaces (gyms, auditoriums and cafeterias); CO2 sensors; match outside air to actual occupancy.
- Right-sizing boilers and chillers.
- Minimizing pump and fan power.
- Dehumidifying without reheat.
- Avoiding simultaneously heating and cooling
- Implementing a good lighting design – with a 50 footcandle target for classrooms.

Two Pipe: Design Principles

By way of summarizing key elements of the new approach to designing two pipe systems, it is useful to list some rules of thumb:

- Keep all elements of the design as simple as possible consistent with maintaining health, safety, comfort, good energy performance, and long-term cost effectiveness. Well placed sensors in conjunction with smart controls manipulated via mathematically sophisticated algorithms can often enable simplicity of hardware. Straightforward hardware is less expensive and easier to understand, install, and maintain.
- Study the building as a whole, quantifying the space conditioning needs and patterns of energy use as a function of each zone. Use this intelligence information to adopt an overall energy efficiency strategy before specifying equipment for the HVAC system. For school retrofits, it's usually quite cost effective to replace old T-12 lighting fixtures with T-8 or T-5-based fixtures with electronic ballasts. This strategy both directly cuts electric energy use and lightens the air conditioning load.
- Design the two pipe HVAC system to meet the cooling load. This affects the size of the chiller, the size of the unit ventilators, and the rate of pumping chilled water (which determines the size of the circulation pump.) After the cooling load is met, the heating system design can be completed by specifying a boiler combination that will supply adequate heating on the design day.
- Choose equipment with a view to good performance vis-à-vis other elements of the system, energy efficiency, maintainability, long life, and low cost (in that order). The big ticket key system elements are boilers, chillers, and unit ventilators. Highly efficient, low volume condensing boilers that can be modulated down to 6 percent of their full rated output with no loss in efficiency are a real bargain. Chillers with "fuzzy logic" that allows flexibility in operating conditions (including accepting return water at 100 F for brief periods) are desirable. Unit ventilators with direct digital control over face and bypass settings and fan speeds are key to maintaining indoor air quality and comfort efficiently.
- Minimize pipe losses by using large diameter, well insulated pipe, keeping runs as straight as practical, and eliminating as many valves as possible. This saves money, pumping power, and maintenance headaches.
- Install a reliable energy management system (EMS). This plays many roles, from modulating boiler temperatures as an inverse function of outside air temperatures to maximizing system efficiency. An EMS is necessary for monitoring and displaying temperatures and flow rates throughout the system as a part of a continuous commissioning process. The system must be capable of automatically controlling the switchover from heating to cooling (and back again), setting flags when values are out of tolerance, and displaying information that enhances the effectiveness of both routine and special maintenance work.
- Set up the new system and commission it with attention to detail. In addition to hardware, sensors, and control software, the commission process needs to include a human element. All users—janitors, teachers, maintenance people, and principals—need to understand enough about the system to play an active role in ensuring comfort and efficiency.
- Train maintenance staff to know and love their new two-pipe HVAC system--and to take care of it. Integrating maintenance people into an operators' group such as the T-POG in Indiana is particularly empowering.

Summary

The "new" two-pipe HVAC system is proving to be a wonderful solution to a number of energy problems in institutional and other buildings, both retrofit and new,, but it isn't the right solution to every problem. In those situations where it is most applicable, like traditional school buildings, two-pipe is proving to be less expensive to build, less expensive to operate and less expensive to maintain than any other option for heating and cooling. When properly applied, there are no compromises in occupant comfort, indoor air quality, or humidity control.

Modern digital controls and creative design have solved the workability issues, and made this once forgotten system a smart choice for the 21st century. As cities begin to modernize older urban schools, two-pipe will allow them to update four schools for the price of three using other technologies, and two-pipe will probably result in lower utility bills.

References

Durkin, Thomas August 1999. "Take a Fresh Look at Face and Bypass" In Heating/Piping/AirConditioning Engineering.

Kinney, Larry. 2001. *Two-Pipe HVAC: It May be Twice as Good As Four*. ER-01-13. Boulder, Colorado: E source