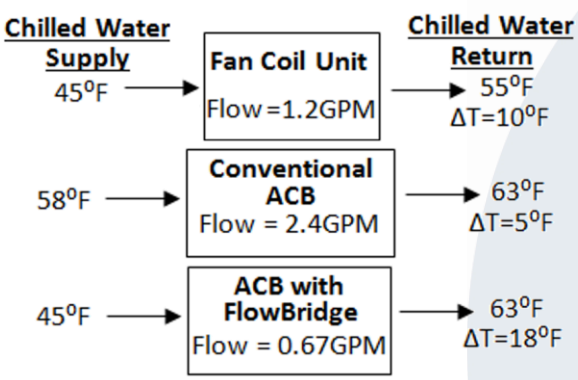
A Healthy HVAC System for People and the Planet

This white paper describes how the advantages of the FlowBridge™, a novel control system for hydronic terminal units, in combination with energy recovery DOAS units can provide a healthy HVAC system for people and the planet.

Executive Summary

Current HVAC systems are not healthy for people or the planet. Indoor Air Quality (IAQ) is compromised by high levels of pollutants, air ducts provide conditions that are conducive to the growth of mold and mildew, and energy inefficiencies needlessly consume excessive amounts of fossil fuels. The COVID-19 pandemic has magnified the need for effective HVAC technologies, particularly with respect to IAQ.

Active chilled beams (ACBs) and Sensible Cooling Terminal Units (SCTUs) utilizing a dedicated outdoor air system (DOAS) are promising technologies to improve IAQ, but significant shortcomings in the control systems have made these systems expensive to design, install, operate, and maintain. The FlowBridge™ by FT Energy Controls, LLC (FTEC) has demonstrated an improved controller that not only significantly reduces these costs but also provides a comfortable indoor climate with improved IAQ and reduced energy consumption [1]. A key innovation of the FlowBridge is to immediately recirculate and mix with the chilled water supply a portion of the return flow from each terminal unit back into the terminal unit. The cost of the FlowBridge makes it practical to install the controller with each terminal unit or each group of terminal units in a zone. Testing of the FlowBridge has further shown the potential to increase the rate of cooling by over 60% compared to equivalent conventional ACB systems while continuing to avoid harmful condensation in the ACB. A prototype system has been developed, built, and tested to demonstrate performance. The FlowBridge can provide savings in all lifecycle stages, and improved comfort and IAQ, likely displacing many conventional technologies. Figure 1 illustrates increased delta T and increased cooling capacity achieved with the FlowBridge.



Control Method	Conventional ACB	Flowbridge ACB
Air Flow (CFM)	288	288
Coil Inlet Temp. (°F)	75.8	75.4
Coil Outlet Temp. (°F)	64.3	56.9
Cooling Capacity (Btu/hr)	3,577	5,754

Cooling Capacity Increase: 2,177 Btu/hr (61%)

Figure 1: (left) Comparison of typical operating conditions for a fan coil unit (FCU), ACB with conventional controller, and ACB with the FlowBridge. The FlowBridge provides the highest delta T and lowest flow rate. (right) Experimental data illustrating the increased cooling capacity of an ACB using the FlowBridge. A smaller ACBs can be used to meet demand with the FlowBridge.

Background on HVAC Systems, Energy Recovery, ACBs and SCTUs

It is important to understand the problems with conventional HVAC systems and conventional controls for ACB and SCTU systems. The goal of the FlowBridge is to overcome these problems so that an HVAC system can be both healthy for people and the planet.

The main reason that existing HVAC systems have poor IAQ and energy efficiency is that our buildings have changed but the HVAC technology has not effectively responded. The first change came as a result of the energy crises of 1973 and 1978. To reduce energy consumption, building envelopes were required to be tighter to reduce energy losses. As a consequence, there was less air infiltration into and out of buildings which created the IAQ problems. To overcome these IAQ challenges, there are now building code requirements to bring in more outside (fresh) air. Unfortunately, this outside air requires significant amounts of energy to condition it to the proper conditions of temperature and humidity for personal comfort.

The problems of unhealthy IAQ and excessive energy consumption have been increased by the recent COVID-19 pandemic and the need to provide additional outdoor air for ventilation. Fortunately, technological advances have been made in systems that condition outdoor air. Traditionally these systems have been called Dedicated Outdoor Air Systems (DOAS) with the purpose of only conditioning the outdoor air to acceptable indoor conditions. More recently, DOAS manufacturers have incorporated energy recovery systems into their equipment that significantly reduces energy consumption by making use of both the sensible energy and the latent energy in the air that is exhausted from the building.

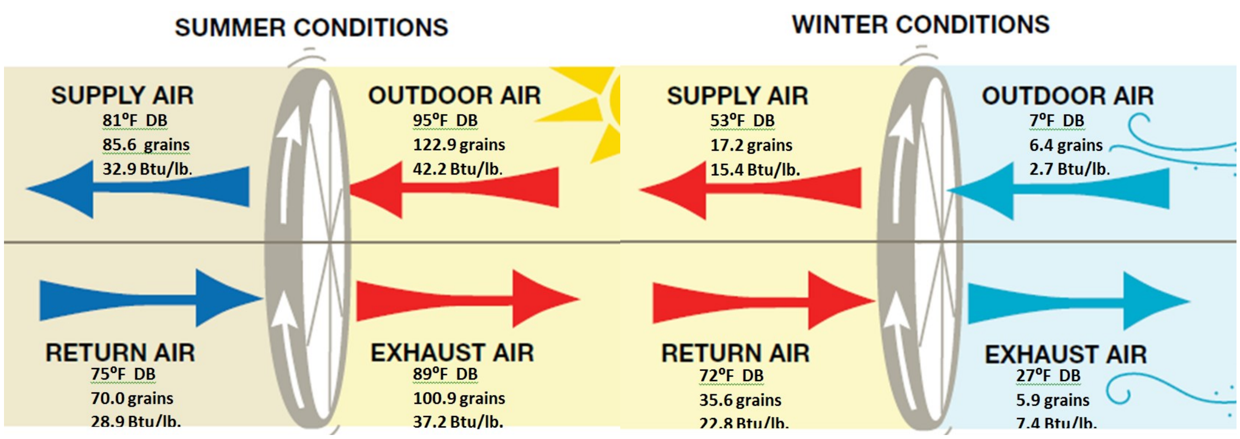


Figure 2: Example conditions for the operation of an enthalpy wheel as part of an energy recovery ventilator (ERV) during (left) summer and (right) winter conditions. Image from [2].

Figure 2 shows how the use of an enthalpy wheel can exchange both temperature and humidity from the return air to condition incoming outdoor air. During summer conditions, this Energy Recovery Ventilator (ERV) reduces the temperature of the outdoor air from 95°F to 81°F and reduces the amount of moisture in the air from 122.9 grains of moisture per pound of dry air (gr./lb.) to 85.6 gr./lb. which reduces the enthalpy (sum of sensible and latent energy) of the outdoor air from 42.2 Btu/lb. to 32.9 Btu/lb. The enthalpy of a typical conditioned space is 28.2 Btu/lb. at 75°F and 50% relative humidity (RH). Therefore, by making use of the energy that is exhausted from the building, this ERV can reduce about 70% (i.e., (42.2 - 32.9) / (42.2 - 28.9)) of the energy needed to condition the ventilation air at these summer conditions. Similarly, for winter conditions, this ERV can reduce about 63% of the energy needed to condition the ventilation air to 72°F and 30% RH while the moisture content of the outside air is increased which is desirable.

Some manufacturers are using enthalpy wheels in combination with desiccant wheels and cooling coils to obtain very low humidity levels. Figure 3 shows an energy recovery DOAS that can supply ventilation air with all of the latent cooling (moisture removal) that is needed for humidity control. In this example, the energy recovery DOAS conditions outside air from 95°F to 62°F and from 118.1 grains to only 45.0 grains which can provide all of the latent cooling and some of the sensible cooling needed for the building. By making use of energy recovery the amount of cooling energy needed is reduced from 89 tons of cooling to 42.1 tons of cooling. This is a 53% reduction in the amount of cooling needed to produce the supply air from the outside air.

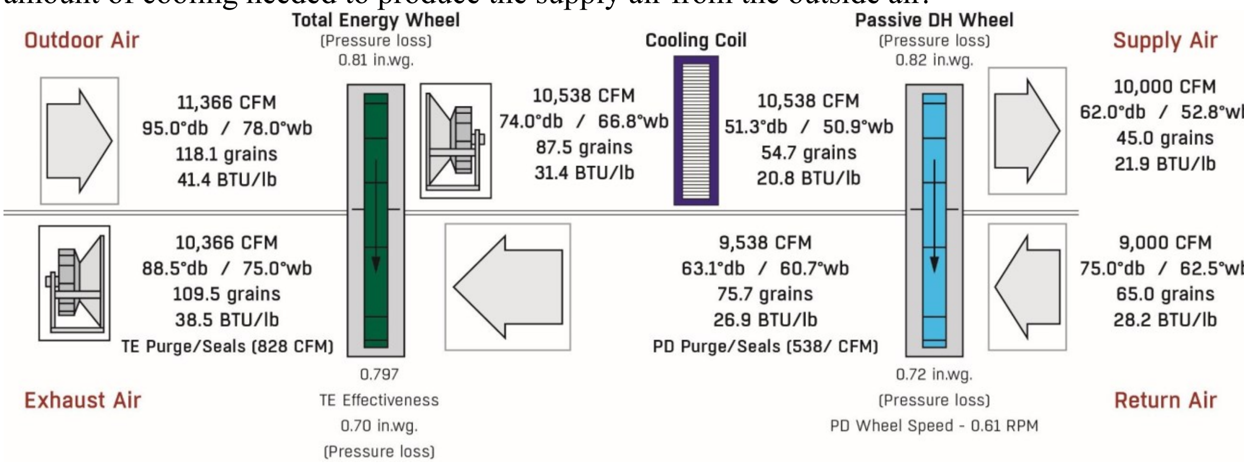


Figure 3: Example operation and conditions for an Energy Recover DOAS. Dry bulb (DB) and wet bulb (WB) temperatures in degrees Fahrenheit. Note that the equivalent load without energy recovery is 1,073 MBH, which is reduced to 505 MBH with the use of energy recovery. This reduces the amount of cooling needed from 89 tons to 42 tons. TE - Total Energy/Enthalpy; DH - Dehumidification; PD - Passive Desiccant. Image from [3].

If adequate latent cooling (i.e., removal of humidity) is performed by the energy recovery DOAS and not by the cooling coil in the rooms of the building, the room coil need only provide sensible cooling (i.e., temperature reduction). There should be no condensate (liquid water) in the room coil, significantly reducing the possibility that mold and mildew can survive in the room. With no liquid water present, the problem of mold and mildew in the ducts and equipment can be eliminated. Further there is no need for condensate pans and drainage systems from each room.

The energy recovery DOAS technology has demonstrated an effective means of reducing energy costs and has allowed for the downsizing of chillers and boilers. Additionally, these systems allow for the indoor environment to maintain a more comfortable humidity level. The supply air from an energy recovery DOAS can be used as the primary air by an ACB to induce air flow across its cooling coil. This eliminates the need for a fan near the coil. With no fans and no compressors in the rooms, this system is much quieter. Figure 4 shows a cross-sectional view of an ACB and describes its operation with primary air from an energy recovery DOAS.

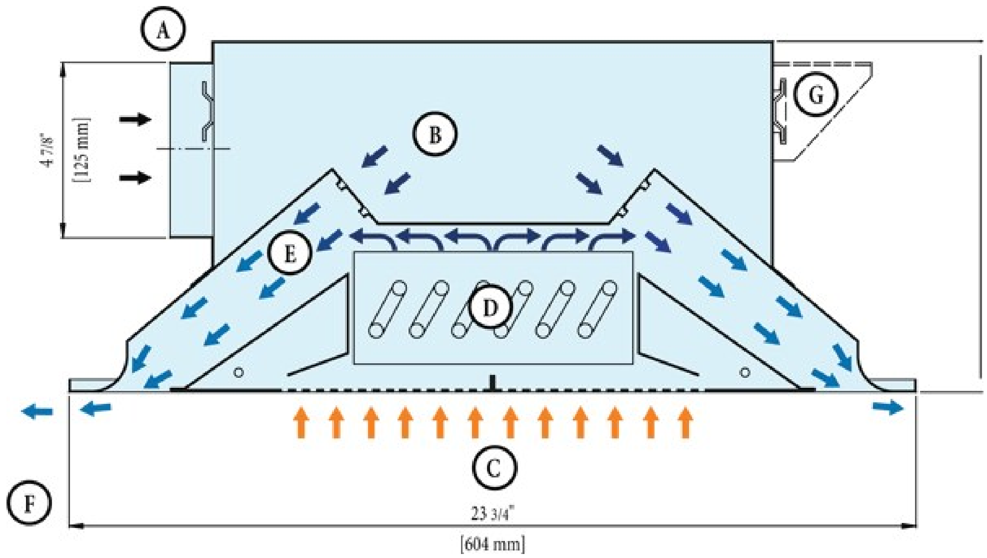


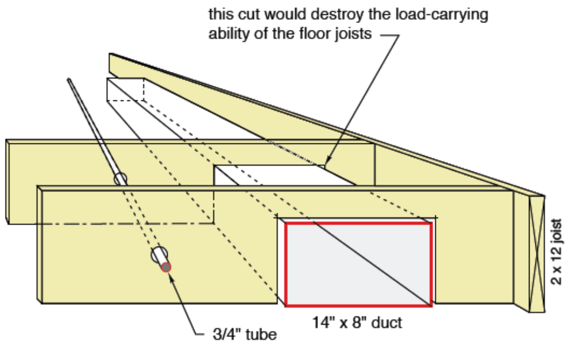
Figure 4: Cross-sectional view of an exemplary ACB. Warm room (secondary) air (C) rises and passes through the cooling coil (D) which is a winding of pipes flowing with cooling water. Primary air provided by an energy recovery DOAS (not shown) passes through the duct collar (A) and into the primary air plenum (B). Positive pressure on the primary air forces it through nozzles, mixing it with the secondary air and inducing an increased flow of room air through the cooling coil. The mixed air (E) is discharged (F) back into the room. Image from [4].

The temperature of the water running through the cooling coil can be controlled depending on the cooling loads of the conditioned space. The water temperature supplied to conventional ACBs is designed to be a few degrees higher than the air dew point to avoid any condensation on the coil. A typical chiller discharge temperature is between 42 and 45°F (average 44°F). To avoid condensation on the coil, the typical entering water temperature to the chilled beams is currently controlled between 56 and 60°F (average 58°F).

It is important to consider all of the ways that energy is consumed by an HVAC system. This includes the chillers and boilers that produce the cooling and the heating. It also includes the systems that make use of this energy, like the energy recovery DOAS and the ACB. In the case of the energy recovery DOAS, this paper has already described how the utilization efficiency can be dramatically reduced by recovering the energy from the conditioned, exhaust air. Another way that energy is consumed is by the method that the cooling and heating is distributed within the building. This is called the distribution energy efficiency. Figure 5 shows that because water has a much higher heat capacity than air, it is able to distribute cooling and heating within a building in a much smaller volume. To transport the same amount of cooling or heating with air requires 3500 times as much volume than water.

This difference has two important consequences. It requires much less energy to transport energy with water using a pump than with air using a fan. Figure 6 shows that to transport 10 tons of cooling with air requires 5.2 brake horsepower (BHP) compared to 0.8 BHP with water. For this example, it takes 6.5 times as much energy to transport 10 tons of cooling by air than by water.

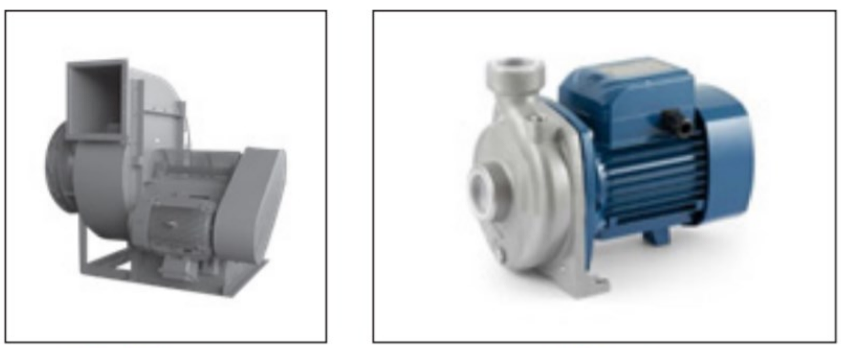
Material	Specific heat (Btu/lb/°F)	Density* (lb/ft³)	Heat capacity (Btu/ft³/°F)
Water	1.00	62.4	62.4
Concrete	0.21	140	29.4
Steel	0.12	489	58.7
Wood (fir)	0.65	27	17.6
Ice	0.49	57.5	28.2
Air	0.24	0.074	0.018
Gypsum	0.26	78	20.3
Sand	0.1	94.6	9.5
Alcohol	0.68	49.3	33.5



$$\frac{62.4}{0.018} = 3467 \approx 3500$$

A given volume of water can absorb almost 3500 times as much heat as the same volume of air, when both undergo the same temperature change

Figure 5: Water has a heat capacity almost 3,500 times that of air making it a much more efficient medium for heat transfer. Image from [5]



550 CFM = 1 ton

$$BHP = \frac{CFM \times SP}{6{,}356 \times FAN_{EFF}}$$

Fan BHP to move 10 tons of cooling = 5.2

Assumes fan SP of 4.5 inches and efficiency of 75%

4GPM = 1 ton

$$BHP = \frac{GPM \times HD}{3{,}960 \times PUMP_{EFF}}$$

Pump BHP to move 10 tons of cooling = 0.8

Assumes head loss of 60ft. and 75% pump efficiency

Figure 6: Comparison of energy used to transport cooling with air versus water. Image from [6]

It also requires much less building space to transport energy with water than with air. The building space that is saved can be used for other purposes such as more usable space, higher ceiling heights or more floors per building height. Many conventional HVAC systems use air as their energy transport method. By using water as its energy transport method, ACBs reduce energy consumption and make more space available as shown in Figures 7 and 8.

There are other advantages associated with the use of ACBs. ACBs do not require fans, and thus contribute to reduced maintenance requirements and reduced noise. ACBs also have the potential to make the cooling and heating needs of each conditioned space independent. With central air handlers, the air volumes need to be increased if one space requires more cooling. With ACBs, the temperature of the water feeding each chilled beam can be reduced, resulting in substantial energy savings. Furthermore, by not recirculating the air back to a central air handler the risk of spreading COVID-19 and other contaminants to other rooms is significantly reduced.

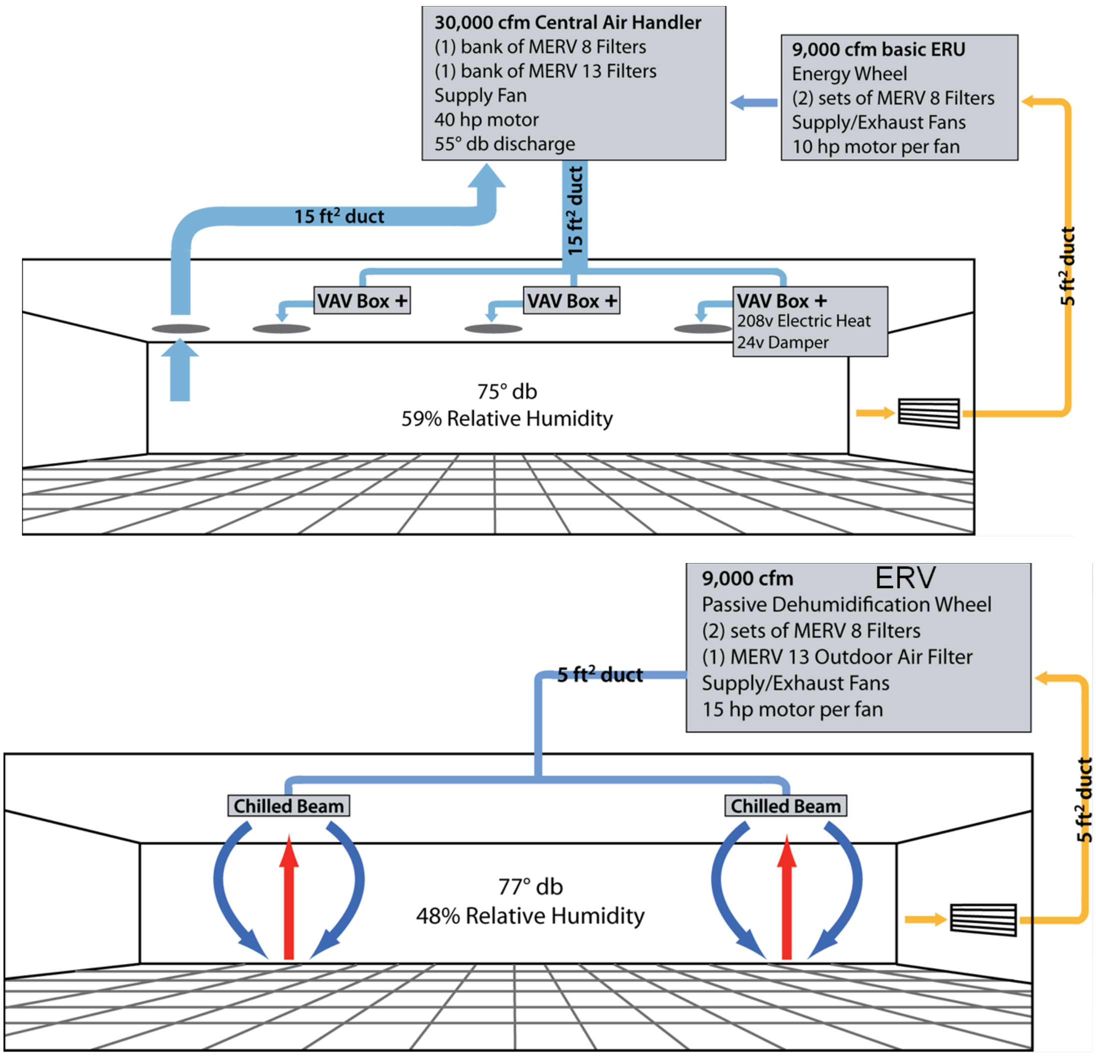


Figure 7: Comparison of (top) conventional variable air volume (VAV) system and (bottom) ACB system, both using energy recovery DOAS, labelled as ERU (energy recovery unit) and ERV. Adapted from [3].

Another advantage of using ACB with DOAS units is the much smaller volumes of air that are needed. Figure 7 shows simplified comparisons of the equipment and ducts required for a conventional variable air volume (VAV) system with an energy recovery DOAS and an ACB system with an energy recovery DOAS. Notably the ACB system eliminates the need for the central air handler and its dedicated return duct. Also, the supply air ducts are reduced in size by a factor of three. Overall, the ACB system can reduce equipment costs, installation costs, and energy consumption, while at the same time providing more usable building space by eliminating these large components of the VAV system.

Figure 7 shows that the total air flow rate for this VAV system is 30,000 CFM compared to the total air flow rate for the ACB system of only 9,000 CFM. Therefore the ACB system only requires

30% of the air flow of the VAV system. All of the recirculation air flow for the ACBs is provided by induction and therefore does not require any additional fan energy. The ACB system provides a significant reduction in the distribution energy required for heating and cooling.

Figure 8 compares the costs for energy by three different HVAC systems for a 140,000 sq. ft. school building. Specifically, the figure compares the cost of using ERVs (energy recovery DOAS) with water source heat pumps (WSHP) versus ERVs with ACBs. WSHP are another conventional HVAC system, like the VAV system, that uses fan-driven recirculation to transport energy to the individual rooms. Figure 8 shows the largest use of energy is for the fans to distribute the cooling and heating. This fan energy can be reduced from $32,000/yr. to $6,200/yr. by distributing the energy with water rather than air. The cost of energy for cooling, heating and pumping can be reduced from $53,750/yr. to $28,250/yr. by using the best energy recovery DOAS. For this high school, the total cost of energy for the HVAC system can be reduced from $86,250/yr. to $34,500/yr. This is a 60% savings in the annual cost of energy for the HVAC system.

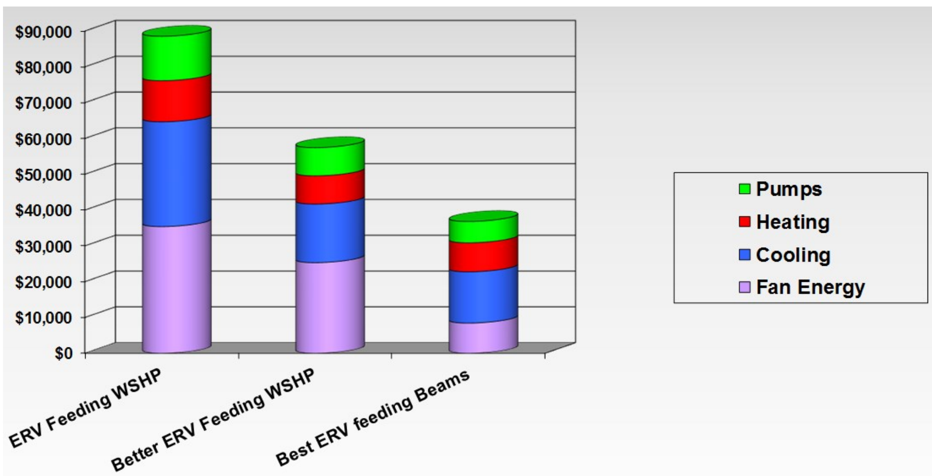


Figure 8: Energy Costs for Conventional HVAC and ACB systems. Image from [3].

The COVID-19 pandemic has made apparent the need to improve indoor air quality (IAQ) in indoor spaces. The use of ACB with energy recovery DOAS units can significantly increase the amount of outdoor air for ventilation versus conventional HVAC system. The amount of ventilation air required by code is dependent upon the occupancy of the rooms. For ACBs the ventilation air must also provide all of the latent cooling and the induction required across the coil for adequate cooling and heating. To meet these two other requirements, the amount of primary (ventilation) air for ACB can be 2.3 times the ventilation air requirement [7]. Providing this additional ventilation air at the higher static pressures needed for induction increases the energy consumption of the DOAS units.

SCTUs are similar to ACBs since both systems provide sensible cooling only and are controlled to avoid condensation on the coils. One difference is that SCTUs use fans to provide the air flow across the coils rather than induction. To minimize this additional fan energy consumption, Electrically Commutated Motors (ECMs) are used to provide variable air flow rates. The other difference is that SCTUs have flow-measuring ventilation dampers that provide a continuous measurement of the Conditioned Outdoor Air (CA) which can provide variable control of the CA and Demand Controlled Ventilation (DCV). Figure 9 shows a typical SCTU.

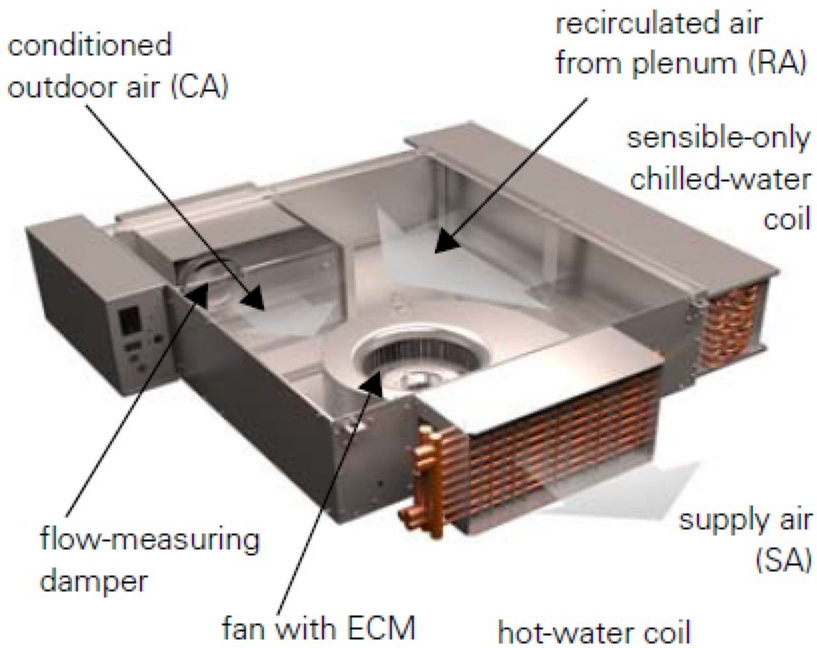


Figure 9: Sensible Cooling Terminal Unit (SCTU) Image from [19]

Figure 10 compares the annual energy costs in 4 cities for 4 different HVAC systems. Both ACBs (# 2 Active Chilled Beams) and SCTUs (#3 CoolSense DOAS by Trane) have significantly lower energy consumption than the traditional Variable Air Volume (#1 ASHRAE 90.1 Baseline VAV) system. By making use of the FlowBridge with both ACBs and SCTUs it will be possible to significantly reduce the energy consumption and the capital costs versus the High Performance VAV (#4) system.

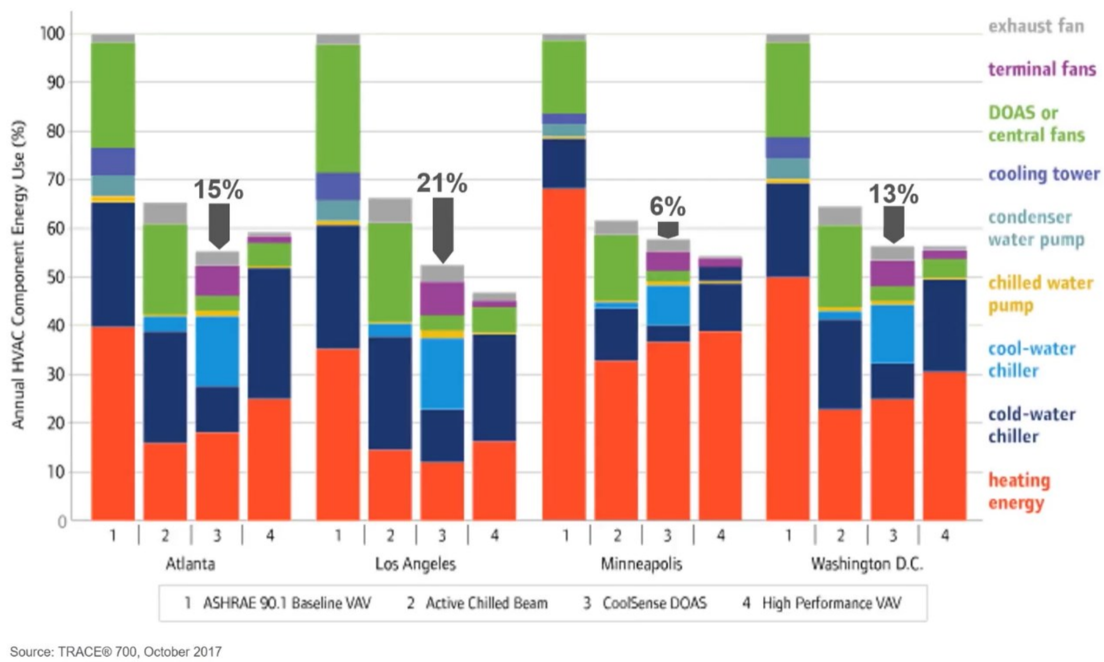


Figure 10: Comparison of the Annual Energy Costs for Different HVAC Systems. Image from [20]

Limitations Preventing Broader Adoption of ACBs and SCTUs

The prior section illustrated many advantages of using ACBs and SCTUs with energy recovery DOAS over alternative HVAC technologies - ACBs and SCTUs can provide more outdoor air, improving IAQ; they avoid condensation, eliminating mold; and they use significantly less energy and they can cost less than other HVAC systems. Still, there are significant shortcomings in current ACB and SCTU implementations which have stifled adoption of these technology. Specifically, ACBs and SCTUs have been underutilized for at least four important reasons:

- **Conventional ACB and SCTU control systems are more costly to design.** ACBs and SCTUs are typically used as an alternative to fan coil units (FCUs). Virtually all design engineering firms and mechanical contractors have a great deal of experience with FCUs, but little, if any, experience with ACBs and SCTUs. Conventional ACB and SCTU control systems are significantly more difficult to design than conventional FCU-based systems because they require the design engineer to specify a secondary piping system which must be custom designed based upon the pressure losses, pipe sizes and pumping requirements for each of the building zones. This is a complicated and time-consuming process which significantly increases the design engineering costs. The FlowBridge eliminates these added design engineering costs by using the same chilled water supply temperatures as FCU. This eliminates the need for the secondary piping loop of conventional ACB and SCTU control systems.
- **Conventional ACB and SCTU control systems cost more to install.** The additional piping, pumping and controls required for the conventional ACBs' and SCTUs' secondary piping systems costs more than the piping system for FCU. This is due to the fact that these secondary loops have flow rates that are double the flow rates for FCU. This increases the costs for pipes, pumps, valves, etc. The use of these secondary loops is new to most mechanical contractors which also increase the installation costs. The FlowBridge eliminates these added installation costs by not requiring any secondary piping.
- **Conventional ACB and SCTU control systems require more energy for pumping.** The flow rates must be doubled to provide the same amount of cooling as FCUs. Larger flow rates mean more energy consumption, larger pumps and piping. Additionally, for ACBs and SCTUs managed in zones with dedicated secondary loops, when switching between heating and cooling the loop is flushed, mixing chilled and hot water. The FlowBridge reduces the energy consumption by pumping lower flow rates than conventional FCU.
- **Conventional ACB and SCTU control systems provide a less comfortable environment.** ACB and SCTU using conventional control systems can be slow to respond to the cooling and heating needs of a building. Zone management means that the ACB and the SCTU in the least favorable conditions (e.g., high humidity environment) will dictate the water temperature that can be used in the entire zone. The FlowBridge increases the rate of cooling by 61% compared to conventional ACB which provides a more comfortable environment.

Fortunately, none of these shortcomings are intrinsic to the ACB and SCTU technology. Rather, they are the result of a poorly implemented control strategy. FTEC's FlowBridge™ controller addresses these critical limitations making ACBs and SCTUs a much more compelling choice for HVAC systems.

FTEC's FlowBridge Controller

Figure 11 shows the FlowBridge control system topology. At left the controller connects to a customary four pipe system (hot and cold water supply input and return). At right it connects to a single coil ACB connected to DOAS air supply. The basic concept is that a recirculation pump provides a portion of the return water from the connected ACB back to the input side where it is mixed with supply water to achieve the desired input water temperature. Two electronically controlled valves are used to control the amount of cold (or hot) water from the supply. The temperature of the ACB's input water is monitored to provide feedback to the control valve. Ambient sensors monitor the air conditions, to determine the rate at which cooling or heating should be delivered. Control limits prevent undesirable conditions such as condensation.

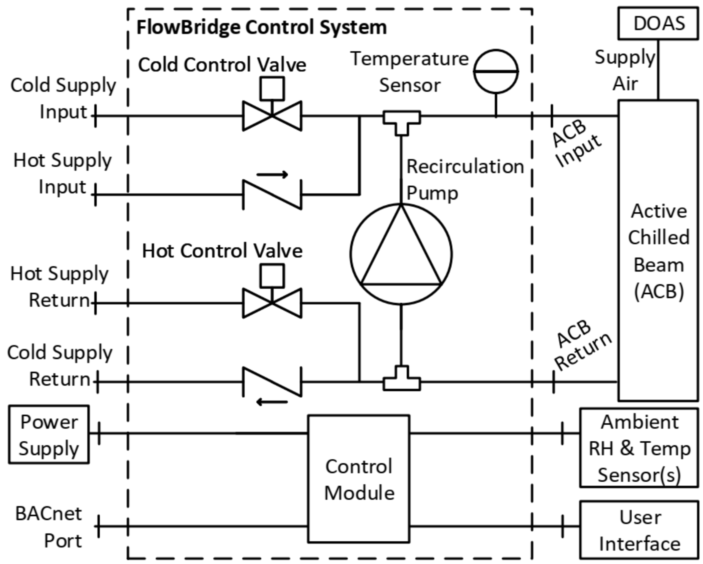


Figure 11: Block Diagram of the FlowBridge Controller. Adapted from [8].

The FlowBridge controller has many advantages over conventional ACB, SCTU and FCU controllers. These advantages are detailed in another white paper [1], but summarized here:

- **The FlowBridge reduces energy consumption, and capital costs by lowering the flow rate and the temperature of the chilled water delivered to each ACB and SCTU.** A typical FCU operates with a change in water temperature of 10°F (e.g., water enters the FCU at 45°F and exits at 55°F) while a typical ACB and SCTU operates with a change in temperature of 5°F (e.g., 58°F input, 63°F output). The FlowBridge operates with a change in temperature of 18˚F (e.g., 45°F input, 63°F output) thus requiring only 56% of the water flow rate of the equivalent FCU (28% of the flow rate for conventional ACBs and SCTUs). The FlowBridge and its terminal units are an alternative for FCUs and design engineers familiar with FCU systems will have no difficulty transitioning to FlowBridge controlled terminal units. This will significantly lower design costs and increase the availability of capable design engineering firms. The FlowBridge also allows a single coil to be used for both cooling and heating eliminating the need for separate coils.
- **Each FlowBridge control system provides the optimum flow rate and temperature of chilled water and hot water to its respective terminal unit independent of the conditions or demands of any other terminal unit.** This improves the comfort within the

space. This is impossible with competitive chilled beam control systems which in all practical implementations rely on a single controller to control multiple terminal units. With the FlowBridge the issue of prioritizing different rooms is eliminated. Each controller simply manages its terminal unit or each zone of terminal units to achieve the respective setpoint in the shortest amount of time without regard to other cooling or heating processes that would be competing with it using conventional controllers. Since each zone is controlled independently it is possible to significantly increase the rate of cooling compared to conventional control techniques (as shown in Figure 1, above).
Conventional controls cool more slowly, in part, because of poor dew point observability. FTEC is implementing a technology in the FlowBridge that can dramatically increase the rate of cooling compared to conventional controllers by accurately determining the dew point within the beam. Specifically, better dew point observability allows for colder input water increasing the beam's input-output temperature differential (ΔT) and thus increasing cooling capacity. This can be translated into cost savings by reducing the size of the beam or the amount of primary air. Further, by controlling the amount of primary air to each terminal unit, it is possible to integrate a Demand Controlled Ventilation (DCV) system based upon CO_2 and/or occupancy sensors.

- **The FlowBridge makes the energy recovery DOAS more practical, improving IAQ, reducing ductwork, and reducing the energy needed for fans and the size of ductwork [1].** Energy recovery DOAS units can provide more fresh outdoor air to terminal units which is conditioned in part by the conditioned, exhaust air. The risk of mold and mildew in the ducts is essentially eliminated because the DOAS air is very dry. Because each zone is individually controlled, the control limits are specific to the conditions in each zone and not dictated by the worst case in the building. This permits for a dramatic increase in the cooling capacity of each terminal unit.

Case Study - Capital Cost Savings by Eliminating Secondary Piping for ACB

Figure 12 shows the differences between HVAC systems designed for FCU, conventional ACBs and the FlowBidge with ACBs.

FCUs typically operate with a ΔT of 10°F while ACBs operate with a ΔT of 5°F. To deliver the same amount of cooling or heating the active chilled beams will need to have flow rates that are two times the flow rates of the FCUs. This requires larger pipes, pumps and valves. This increases the capital costs and the operating cost of using typical chilled beams. The FlowBridge eliminates these added costs and also reduces the piping and pumping costs compared to fan coil units. The FlowBridge operates with a ΔT of 18°F which requires only 56% of the flow rates of typical FCU. This will provide a cost savings when compared to typical fan coil units.

In September 2020, FTEC commissioned Total Industrial Services, Inc. (TIS) to perform a study evaluating piping costs for a representative building (a five story hotel with 24 guest rooms per floor). Specifically, the study compared the piping costs for a conventional ACB system and a FlowBridge ACB system. TIS estimated a cost savings of $1,278 per chilled beam in piping costs alone (materials and labor). This is a 22% cost reduction for the total piping cost for the HVAC system. Of course, lower flow rates will also allow for the use of smaller pumps and valves, leading to further cost savings relative to conventional hydronic systems. The FlowBidge controller with ACB can use the same piping system as the FCUs and the DOAS. Thus the professional design costs should be practically identical to those of a conventional FCU-based system. Further discussion of conventional control technologies are provided in references [6, 7 and 9-18]. The costs for these conventional control systems are too high to have a dedicated controller for each chilled beam.

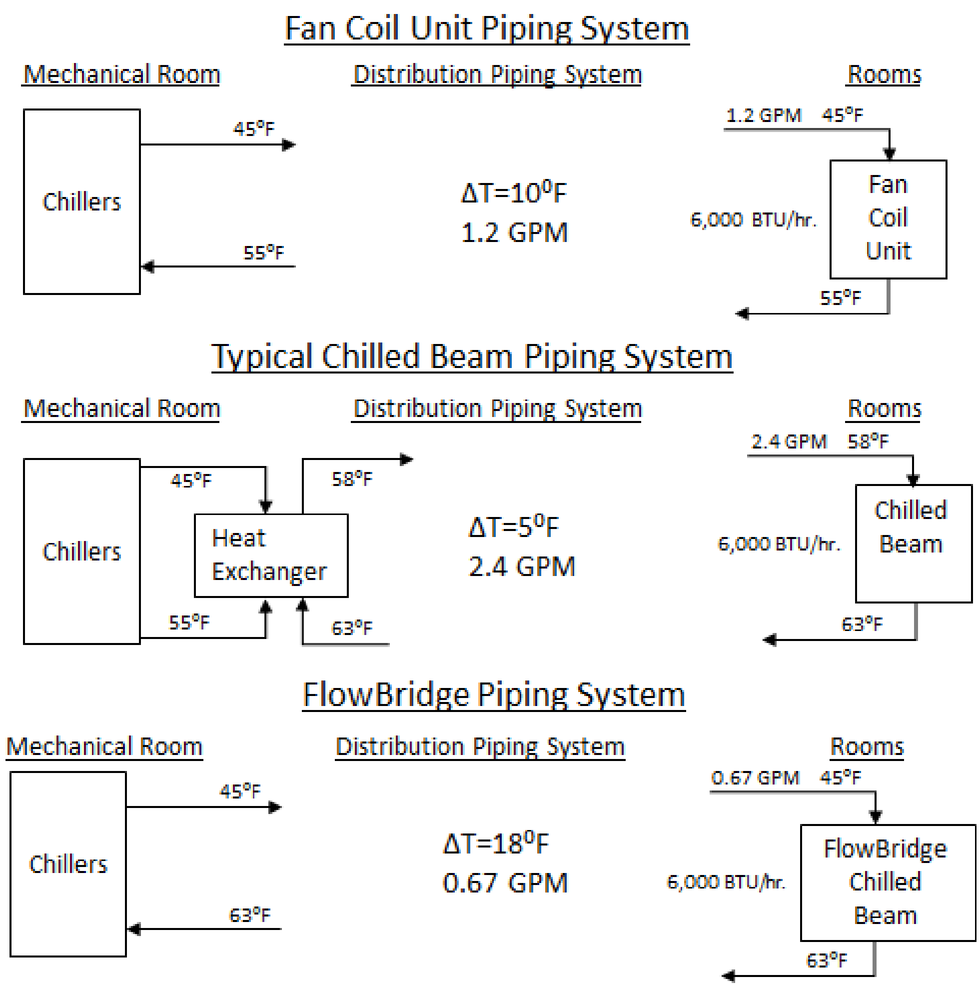


Figure 12: Differences in Flowrates and Temperature for FCU, ACB and FlowBridge.

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About FT Energy Controls, LLC

FT Energy Controls (FTEC) is based in Pittsburgh, PA. The FlowBridge is FTEC's flagship product line with multiple patents pending. If you would like to learn more about FTEC's products and technologies including purchasing and licensing opportunities please contact us.

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