Energy-Efficient Approach For Operating Rooms

BY PHILIP BARTHOLOMEW, P.E.

Hospital operating room HVAC systems require high quantities of circulated air to meet ASHRAE Standard 170[1] and the non-aspirating flow requirements of the operating room. The typical HVAC system is highly ineffective, in terms of energy use, at maintaining the desirable temperature and humidity conditions of the space. This article will demonstrate that a version of a dual duct HVAC system will save considerable amounts of operational energy compared to the standard system.

The typical HVAC system used in operating rooms can be described as a single duct, VAV reheat system (*Figure 1*). A better description is a two position, constant volume reheat system. The system delivers a constant 20 ach to the operating rooms when they are occupied. A higher rate is required if the cooling load dictates or if a special airflow condition is required by the operation being performed. During unoccupied periods, a constant minimum airflow is required to maintain operating room pressurization.

The constant volume reheat aspect of this system has historically been recognized as an energy inefficient system. However, the high airflow requirements of the operating room makes these inefficiencies far greater than those that occur by oversizing the system above what is required to meet the space cooling load.

Note that the dual duct system in *Figure 2* has two separate air tunnels and two separate banks of supply fans. This is required to achieve the energy savings of the system and to allow for an arrangement that locates the supply fan between the cooling coil and the final HEPA filters. Placing the fan in this position allows the fan heat to be added to the nearly saturated air leaving the cooling coil and eliminates biological growth in the HEPA filters.

The dual duct system could be based on a single custom rooftop unit incorporating all components shown in *Figure 2*. Alternately, the system could consist of a separate cooling air-handling unit, a heating air-handling unit and a heat recovery minimum outside ventilation air package. The configuration can be tailored to suit the actual physical requirements.

The two fan arrangement of the system shown in *Figure 2* is considerably different in configuration and operating characteristics than a dual duct unit with a single blow-through fan. In the single fan system, the air path

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diverges after the fan into a separate cold deck and hot deck. The single fan system generally requires active heating of the hot air deck, mixing of hot and cold airstreams at the terminal and allows air that is not dehumidified to enter the space through the hot deck.

A discussion of the minimum outside air portion of the two fan dual duct system, the function of the air-handling unit warm deck heating coil and terminal reheat coil will follow later after the establishment of the energy use advantages of the system.

With the two fan dual duct system, the cold deck produces only the amount of cooling supply air needed to meet the load requirements of the spaces. The remainder of the supply air quantity required to meet the minimum airflow requirement is recirculated, HEPA-filtered air from the warm deck of the unit. Note the heating coil in this air tunnel is not energized for the vast majority of system operation.

FIGURE 1 VAV air unit.

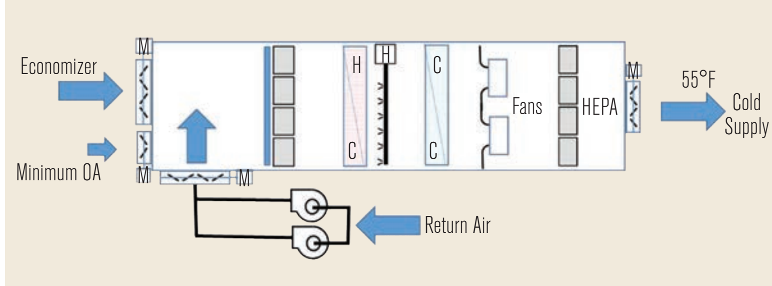
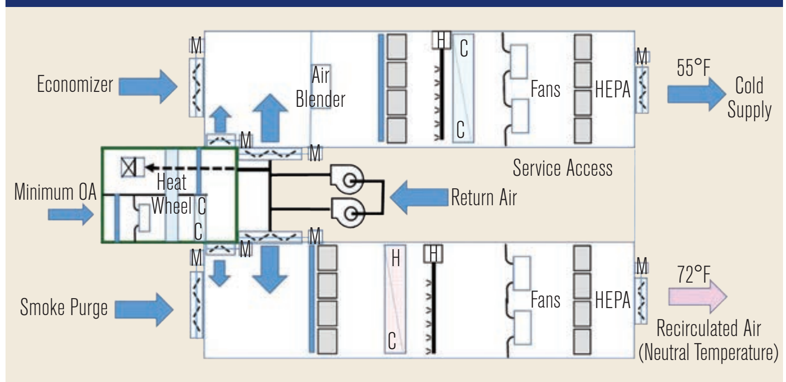


FIGURE 2 Dual-duct air unit.



VAV System Operation

The VAV two-position system produces about 54°F (12°C) supply air (50°F [10°C] coil leaving temperature plus 4°F [2°C] fan heat) 24 hours a day, all year, to be distributed to the VAV reheat terminals. During the unoccupied periods, when the space humidity requirements can be relaxed, the discharge temperature can be reset to 60°F (15°C). The quantity of supply air is generally 20 ach during occupied periods and 10 ach during unoccupied periods.

With the VAV two-position system providing more air to the space than required to meet the heat load, the temperature of the space would be lower than desired. Reheat is introduced to maintain the space temperature setpoint. The reheat quantity would be zero if the cooling capacity of the supply air at 54°F (12°C) exactly meets the cooling requirements of the space. This is, however, almost never the case.

The design cooling load of the typical (not robotic or hybrid) operating room requires only about 12 ach of cooling capacity to maintain a general operating room temperature of 65°F (18°C). Also, this is the design heat load with all equipment in operation at nameplate capacity. There is some diversity, over time, of this equipment load. An even larger factor in reducing the average heat load from design is that the operating room is not in use for a large portion of the occupied period and the only heat load may be the small load of the general lighting.

When the space equipment heat load is not equal to the cooling capacity of the supply air, all the difference in capacity must be offset with reheat to maintain space temperature. To meet the actual cooling load of the space, extra cooling energy is spent to cool all the air circulated and then reheat is added back into the airstream to compensate for the overcooling of the supply air. The sum of the overcooling and subsequent reheating is more energy than the actual cooling load of the space.

Dual Duct System Operation

As stated earlier, the design of the two fan dual duct system leads to the cooling capacity matching the heat load of the spaces and requires no reheat to maintain space temperature in most cases. Both the VAV and dual duct systems require approximately the same amount of fan power since both require 20 ach of circulated air during occupied periods.

There are some savings in supply fan power of the dual duct system since the two air tunnels operate at part

capacity almost all of the time. As a result, there will be a reduced pressure drop that the fans must work against compared to the VAV system. The savings in the supply fan operation more than offset the additional energy required to operate the fans used for heat recovery. Also, within the air-handling units there is an almost equal amount of cooling energy expended to overcome the heat associated with the system fans compared to the VAV system.

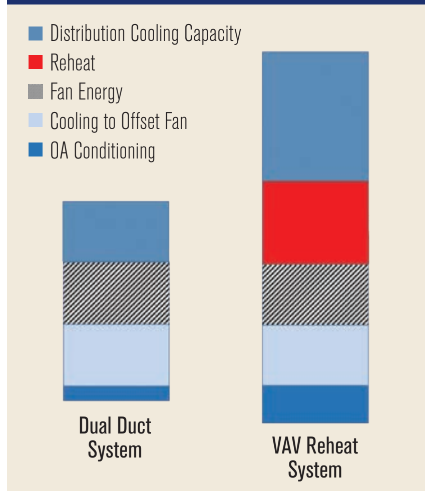
The minimum outside air system for the dual duct system has a total energy heat wheel and a chilled water cooling coil to precondition the ventilation air delivered to the unit decks. As described later, this is required for proper operation of the dual duct system, but not for the VAV system. The savings in thermal energy associated with this requirement is seen in the energy analysis comparison.

Comparison Of Energy Requirements

The energy analysis comparing the two systems was performed for a surgery suite replacement project in western North Carolina. The suite consisted of seven operating rooms, a perimeter corridor, sterile supply and storage spaces. The total floor area of the operating rooms is 4,900 ft^2 (455 m^2), and the area of the other spaces is 4,300 ft^2 (390 m^2). The AHU system capacity was approximately 26,000 cfm (12 270 L/s).

For the comparison the operating room parameters required for both systems are as follows:

FIGURE 3 System energy use requirements at air-handling unit for 75°F average temperature.



- The operating suite was considered a totally interior space with no wall, window or roof thermal loads.

- The operating suite was assumed to be in occupied mode from 6 a.m. to 5 p.m., Monday through Friday. The suite was provided full ventilation air during this time and the VAV and dual duct system cold deck supply air temperature was 54°F (12°C).
- Operations were potentially performed from 6 a.m. to 3 p.m. The actual use of the operating rooms was assumed to be 65% of that time, and the supply air circulation was 20 ach to operating rooms that were actively in use, and 10 ach when not actively in use.
- Clean up was assumed to be from 3 to 5 p.m. During this period, the supply air circulation to the operating rooms was 10 ach.
- The operating suite was assumed to be in unoccupied mode from 5 p.m. to 6 a.m., Monday through Friday and all weekend. During this period, the ventilation air at the air-handling unit was shut off, the VAV unit discharge was reset to 60°F (18°C) and the circulation rate to the operating rooms was 10 ach.
- No operating rooms had robotic or hybrid equipment loads for this simulation.

Figure 3 shows a comparison of the total energy required to operate the VAV and the dual duct systems during a week when the average temperature was 75°F (24°C)—85°F (29°C) daytime and 65°F (18°C) nighttime. This ambient temperature was chosen to better demonstrate a more complete load on the heating and

TABLE 1 Yearly energy requirements for systems.

	DUAL DUCT	VAV (TWO POSITION)
Cooling Energy (MMBtu)	364	898
Fan Energy (MMBtu)	443	489
Reheat Energy (MMBtu)	0	420
Humidification Energy (MMBtu)	31	57
Total (MMBtu)	838	1,864

TABLE 2 Component cost difference in terms of increase for dual duct system.

Warm Deck Air-Handling Unit and Controls	$120,000
Heat Recovery Package and Controls	$15,000
20 ton Reduction in Air Cooled Chiller Capacity	($40,000)
Heating Hot Water Generation	($32,000)
Hot Water Distribution Piping Cost	($29,300)
Added Cost of Ductwork	$20,000
Total Differential Cost	$53,700

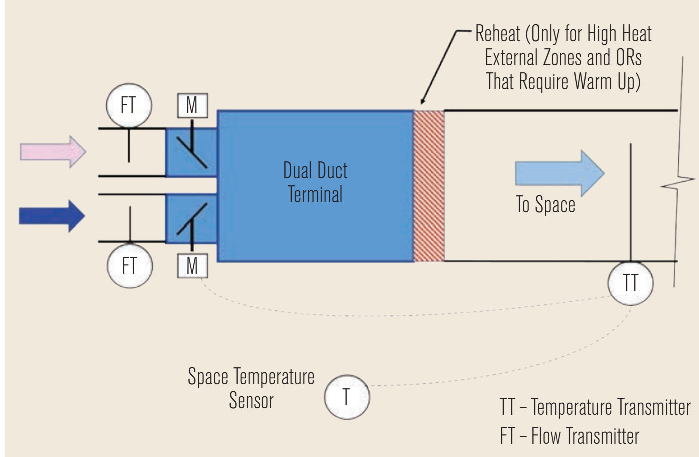
cooling utilities. At lower temperatures, the economizer cycle reduces or eliminates the refrigeration requirements of both systems. The period of one week was chosen to fully account for the influence of the unoccupied mode of operation of the systems. The energy use is expressed in energy requirements at the air-handling unit with no accounting of the chiller plant COP and the efficiency of the boiler plant. The following observations can be made:

- The cooling energy required to condition the outside air was reduced with the heat recovery section of the dual duct system. Although not minor, this reduction was not responsible for the majority of the savings associated with this approach. Conditioning of outdoor air occurs in the main cooling coil of the VAV system. The latent heat transfer of the dual duct system's heat wheel also reduces the amount of winter humidification.
- The fan energy requirements for both systems is approximately equal. This is because the savings due to the dual duct component pressure drop at part flow capacity more than offsets the additional power requirement of the heat recovery fans. Also, the cooling energy needed to compensate for the fan heat is nearly equal in both systems.
- The VAV system's distributed cooling capacity and required reheat energy is very large: subtracting the VAV reheat quantity from the cooling capacity equals the cooling capacity of the dual duct system.

The results in *Figure 3* are for one week. This data extrapolated for one year is shown in *Table 1*.

With estimated utility rates of $0.09/kW for electricity and $9.00/mcf (thousand cubic feet) of gas, the estimated annual energy cost for the dual duct system is $21,100 per year and $34,500 per year for the VAV system.

FIGURE 4 Dual duct terminal controls.



System Construction Cost Comparison and Payback

A cost comparison of the systems was performed based on the specific needs of the project. The needs of the project and the assumptions taken are as follows:

- The cold deck of the dual duct unit consisted of a separate air-handling unit with approximately the same cost as the VAV system air-handling unit. The dual duct cold deck air-handling unit is actually less expensive because it does not require a heating coil and can be downsized to a small degree. For the cost comparison, this difference was not taken into account.
- The warm deck of the dual duct system was an additional cost and consisted of a separate additional air-handling unit.
- The minimum outside air system for the dual duct system was a packaged system with supply and exhaust fans, total energy wheel and cooling coil sized for 4,000 cfm (1900 L/s).
- The project required an air cooled chiller needed for central plant back up capacity. This chiller was to be placed on emergency electrical power.
- A steam to hot water heat exchanger and distribution pumps were required to provide heating hot water to the VAV system reheat loads.

Also it was desirable for maintenance purposes to have the distribution terminals next to the air-handling unit. This helped keep the cost increase of the added duct associated with the dual duct system minimized. The supply duct from the VAV or dual duct terminal to the space is the same for both systems.

Table 2 shows component costs that differ between the dual duct and VAV systems. Component costs such as the return air components and the supply components downstream of the terminal are the same for both systems and are not included below. The cost difference is stated in terms of increased cost of the dual duct system.

The simple payback of the dual duct system for this project is four years. Differences in the control strategy of the VAV system and the use of more outside air can drastically shorten the payback period. Also, differences

in construction costs to suit actual project conditions and requirements will affect the payback period.

Dual Duct Terminal Control

The dual duct terminal schematic is shown in *Figure 4*. For the surgery rooms and other flow/pressure critical areas, the control systems of a standard commercial terminal should be replaced. The flow quantities through the cold and warm inlets to the terminal will have a large variation from near zero flow to full flow. To get accurate flow over this range, it is necessary to use a flow sensor such as a thermal dispersion element as opposed to the terminal-supplied flow cross or flow ring sensor. This will provide an approximate accuracy of 3% over the range and will provide good pressure control of the room.

For temperature control, a discharge temperature sensor is used because the supply air from the terminal is delivered directly onto the patient. This approach allows the space temperature sensor to reset the discharge control setpoint for a less drastic reaction to space condition changes and changes in temperature setpoints. The control of the terminal requires the cold airstream be throttled to match the cooling setpoint of the terminal discharge sensor. The flow quantity of the cold airstream is measured and the warm airstream is throttled so that the sum of the cold and warm airstreams meets the flow requirements of the space.

An auxiliary reheat coil may be desirable for spaces with an exterior skin load or an operating room that may need a quick warm up of the space during the operation, such as a cardiac operating room .

Commercial terminal controls are applicable for areas where the strict flow control of the operating rooms is not required.

Outside Ventilation Air

Because the blend ratio of the two airstreams into the terminal unit will vary greatly, care must be taken that the minimum ventilation quantity delivered to the space is met. The method implemented in *Figure 2* is to bring in a fixed minimum quantity of outside air at the air-handling unit. This quantity is proportioned to the warm

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and cold system airstreams based on the supply airflow of that airstream. This ensures that each airstream has an equal percentage of ventilation air.

The recirculated air being delivered from the warm deck is not cooled and therefore not dehumidified by the components of that deck. The outside air must be cooled and dehumidified before it is delivered to the warm deck to maintain dehumidification of all air delivered to the space. For this function, a heat recovery wheel and cooling coil are used to precondition the outside air before being delivered to both the cold and warm decks.

Warm Deck Heating Coil Operation

The heating coil in the warm deck is not generally required for normal operations of the unit. It is required for the space smoke evacuation mode .

During smoke removal, the air is not returned from the spaces and is exhausted. The unit switches over to 100% outside air to make up the exhausted air. The heating coil must bring potentially cold air up to comfort conditions until patients in other operating rooms of the suite can be evacuated.

In normal system operation, if a majority of the operating rooms are operated at a low temperature, the average return air temperature combined with the cool minimum outside ventilation air may not meet warm air temperature requirements of spaces with a higher temperature setpoint. It may be desirable to have the minimum heating coil leaving temperature set at 72°F (22°C).

For morning warm up periods, this setpoint can be increased to 75°F to 80°F (24°F to 27°C). Note that during the warm up and normal system operating periods the heating capacity is far smaller than during the potential smoke removal operations. Two widely varying sizes of control valves (not just a two-third to one-third split) should be considered for stable system temperature control.

Existing System Replacement/ Modifications

If an existing VAV air system that uses the present standard of 4 ach of ventilation air (approximately 20% of supply), is in place and is at the beginning of its

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service life, the payback of replacing the system does not justify changing to a dual duct system. However, some modifications can greatly affect the operational costs associated with this system. Some suggested modifications include:

- Apply occupancy sensors in the operating rooms so the space has the "occupied" amount of supply air only when the space has an active operation in process. This can be done on a space-by-space basis for most systems and the air-handing unit should be able to respond to the different capacity requirements.
- Reduce the "unoccupied" airflow requirements to those required to maintain operating room pressurization. During the unoccupied period, return air from the operating room can be shut off and all system return can be from the adjacent spaces. Take care to ensure the fans of the system will remain stable at this low airflow.
- Disable hot water to the reheat coils of the system terminals during unoccupied periods. This will eliminate the "fighting" of the cooling and heating components of the system. The space temperature may get cooler than desirable during unoccupied periods. System "occupied mode" start up 30 minutes before an operation begins will result in the reestablishment of normal temperatures.
- Shut down or reduce the outside air ventilation quantity during unoccupied periods.
- Reset the supply air temperature to 60°F during unoccupied periods.

Many of these modifications address the unoccupied operation of the system. It is important to realize that the system operates in the unoccupied mode about two-thirds of the time of yearly operation, and making the changes will have a large yearly savings.

If an existing system was designed to meet older standards requiring 100% outside air, this system is considerably less efficient than the VAV system used as the basis of the analysis above, even if it has a form of sensible heat recovery. Investigation of replacing or modifying this system in the near future should be considered.

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It is possible to add a recirculating warm deck air-handling unit to an existing VAV air system and change out the terminals from single duct reheat to dual duct terminals. This approach is more feasible if there is space for the warm deck air-handling unit and the distribution terminals are in an easily accessible location. Also, careful evaluation of the existing VAV unit fan capacity turndown should be investigated.

Consideration must account for the additional space requirements of the dual duct system in a retrofit situation. Possible solutions may include stacked air handlers or rooftop equipment.

In the evaluation of replacing the existing operating suite system, credit savings in the hospital infrastructure capacity to the replacement system. Considerable savings in boiler and chiller plant capacity will be achieved and this capacity will be available for future additions and renovations. The operating suite needs to be supported by utilities that are on emergency power and this may relate to further infrastructure savings.

Also, if the central plant capacity is judged to be marginal, replacing the operating room system may be a better solution than increasing the capacity of the plant.

Conclusions

It has been demonstrated that the energy demands of an operating room HVAC system can be mitigated by a dual duct air system, as compared to a well-controlled conventional VAV two-position system.

The proposed dual duct system has a higher installed cost, but will provide a favorable payback for many applications.

The changing of the paradigm of what is the optimum system to be applied to the operating room is one of the changes required to address the high energy requirements of the hospital.

References

1. ANSI/ASHRAE/ASHE Standard 170-2008, *Ventilation of Health Care Facilities*. ■