Vertically Integrated Systems in Stand-Alone Multistory Buildings

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The term district energy typically is considered horizontal municipal heating/cooling and domestic piping systems linking thermal production to consumption (*Figure 1*). An alternative approach is to take the system and rotate it 90° to service stand-alone multistory buildings (*Figure 2*).

This involves having production units distribute to the consuming units through a single vertical and central distribution network. Each floor is served by an indirect connected substation (*Figure 3*). Enhancing comfort[1] and reducing energy demand[2] is possible when floor-to-floor (rather than building-to-building) consumption is moderate (cooling) or low (heating) temp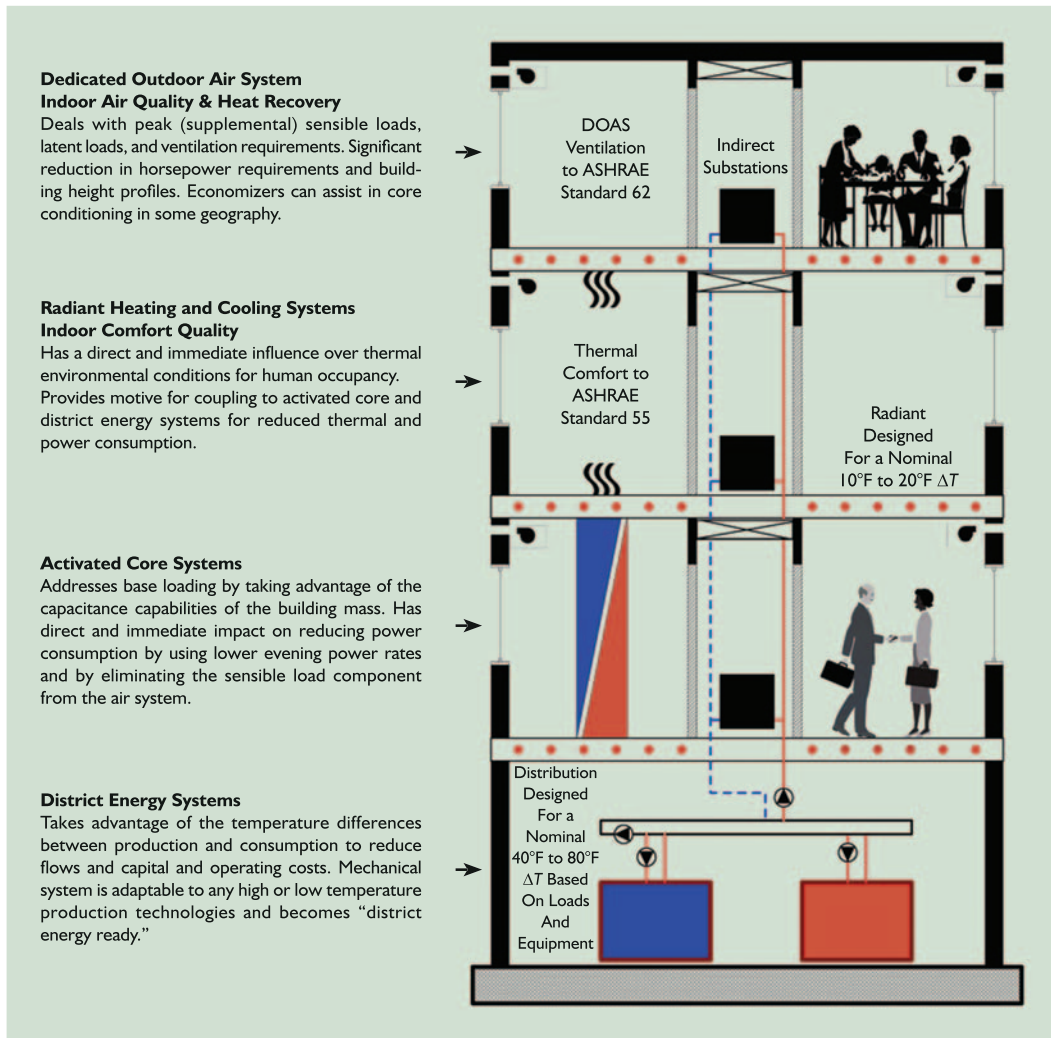erature radiant-based surface conditioning systems are used (possibly with dedicated outdoor air systems). This is particularly true when the design considers activating the building floor mass as a thermal capacitor.

In a vertically integrated system, the heating and cooling plant acknowledges the low-temperature requirements associated with radiant-based systems and is designed to take advantage of condensing or renewable technologies or use standard boiler and chiller equipment.

As noted by Olesen, "Hydronic concrete slab cooling and heating systems can use relative high water temperatures for cooling and relative low water temperature for heating. This increases the possibility of using renewable energy sources such as ground heat exchangers, solar energy for heating and cooling and free night cooling. It also increases the efficiency of boilers, refrigeration machines and heat pumps (Steimle, 1999). On top of that the active concrete system may

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Dedicated Outdoor Air System
Indoor Air Quality & Heat Recovery
Deals with peak (supplemental) sensible loads, latent loads, and ventilation requirements. Significant reduction in horsepower requirements and building height profiles. Economizers can assist in core conditioning in some geography.

Radiant Heating and Cooling Systems
Indoor Comfort Quality
Has a direct and immediate influence over thermal environmental conditions for human occupancy. Provides motive for coupling to activated core and district energy systems for reduced thermal and power consumption.

Activated Core Systems
Addresses base loading by taking advantage of the capacitance capabilities of the building mass. Has direct and immediate impact on reducing power consumption by using lower evening power rates and by eliminating the sensible load component from the air system.

District Energy Systems
Takes advantage of the temperature differences between production and consumption to reduce flows and capital and operating costs. Mechanical system is adaptable to any high or low temperature production technologies and becomes "district energy ready."

Summary and benefits of vertically integrated systems (simplified illustration).

use cheaper night rate electricity." [2]

As stated in the *2004 ASHRAE Handbook—HVAC Systems and Equipment*, "Central plants generally have efficient baseload units and less costly peaking equipment for use in extreme loads or emergencies."[3]

Regardless of the plant selection, the potential operating temperature differential between production and consumption could reduce distribution flows significantly. For heating, floors are limited to less than 84°F (29°C) surface temperatures and for cooling, above 66°F (19°C) (ANSI/ASHRAE Standard 55-2004, *Thermal Environmental Conditions for Human Occupancy*). Therefore, plants operating at 180°F (82°C) or chillers at 42°F (6°C) have significant motive force for heat transfer.

Example (*Figure 4*): Given a 1.5 MBtu/h (440 kWh) direct-connected heating load, operating with traditional baseboard or fan/coil units, 180°F (82°C) entering fluid temperatures, and a design ΔTl of 20°F (11°C) equates to flow using:

$$Q_w = q_w / (60 \text{ min/h} \times p_w \times C_p \times \Delta T)$$

where

Q_w = flow, gpm (L/s)
q_w = heat transfer, Btu/h (kWh)
p_w = fluid density, lb/gal, (kg/m^3) (e.g., I-P units 8.2 at 150°F, 8.1 at 180°F)
C_p = specific heat, Btu/lb · °F, (kJ/kg·K)
Q_w = 1.5 MBtu/h/(60 min/h × 8.1 lb/gal × 1 Btu/lb · °F × 20°F)
Q_w = 155 gpm (9.46 L/s)

To stay within friction losses of 1 ft (0.31 m) to 4 ft (1.22 m) per 100 ft (31 m) of pipe and flow velocities of 2 fps (0.61 m/s) to 5 fps (1.5 m/s), the primary distribution pipe would be a 4 in. (100 mm) line.

However, (independent of discussions on energy production efficiencies), plants running at maximum design with weather-compensated target supply temperatures of 180°F (82°C), indirectly connected to a radiant system operating with a sec-

ondary design return temperature of 100°F (38°C) provide for an 80°F (44°C) Δ*T*in the vertical distribution network serving each substation (*Figure 5*). Substituted into the formula, the primary vertical distribution flow becomes:

$$Q_w = 1.5 \text{ MBtu/h}/(60 \text{ min/h} \times \\ 8.2 \text{ lb/gal} \times 1 \text{ Btu/lb} \cdot °F \times 80°F)$$

Q_w = 38 gpm (2.39 L/s) = 75% distribution flow reduction

Using the criteria for velocity and friction loss, the line size is reduced from 4 in. to 2 in. (100 mm to 50 mm) offering considerable savings on capital costs and operating transmission losses. An analysis of pumping horsepower could accept a 2.5 in. (64 mm) pipe, which reduces the head loss from 2.45 ft/100 ft (0.75 m/31 m) to 0.85 ft/100 ft (0.26 m/30 m) while still operating within acceptable velocities.

A single and central distribution line reduces the number of vertical risers, fire-stops, hangers, supports, insulation, and labor, creating further savings on materials typically associated with traditional designs.

Figure 1: Traditional horizontal district energy system.

Reductions in any quantity of assemblies, translates to a corresponding reduction in potential failure points. With indirect connected substations, the quantity of fluid operating at a higher pressure is contained on the production side of the heat exchangers, resulting in significant volume reductions. A reduction in volume renders significantly smaller plant expansion tanks, and savings in fluid conditioning chemicals.

Figure 2: Vertically integrated district energy system.

If the production side is required to operate with glycol for makeup air or preheat/precool units, the reduced volume means less capital and maintenance cost associated with antifreeze.

Since the pressure on the consumption side of the heat exchangers is always low pressure, valves, circulators, expansion tanks, etc., can be standard off-the-shelf components typically found in low-rise residential systems. The low-pressure requirement and consistency in load distribution creates standardization on each floor leading to further simplification in stocking replacement or repair parts.

Regarding consumption side circulators, Ottmer and Rishel found that circulators sized for just the pressure loss imposed at that particular location can reduce total chilled water pump power by 20% to 25% in very large systems,[3] which leads to further positive economic impact on capital costs and ongoing maintenance cycles.

Vertical integrated district energy systems keep all serviceable equipment outside of the suites. Therefore, maintenance

has little impact on occupants. The indirect systems also contain any mechanical failure on the consumption side to a specific site rather than impact the entire plant or other floors.

They also permit fine-tuning of consumption side temperature with weather responsive controls per substation. Energy meters can be used for per floor allocation of energy costs.

Indirect systems also eliminate many difficulties associated with balancing and commissioning since the hydraulics of the production side are separated from the multiple zones on the consumption side. When the plant is piped in a primary/secondary configuration, constant flow can be employed using three-way diverting valves at the substations, making balancing the single distribution riser a simple task.

With all energy consumption equipment mounted within the substation, multizone balancing is carried out from one location, again simplifying the entire balancing and commission process.

Finally, the coordination during cold weather building construction with this type of system often permits the use of the floor system to condition the space rather than having to bring in temporary construction heaters with their associated health and safety issues.

Explored in the next discussion is the concept of shifting district fluid thermal storage concepts to the building mass.
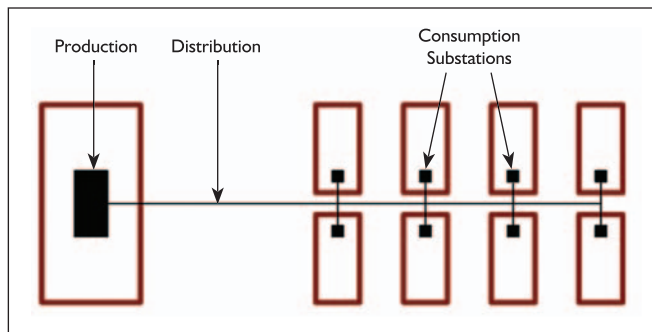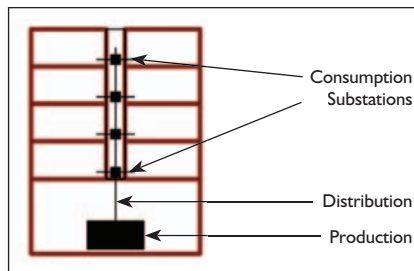
Activated Core

As stated in the ASHRAE Final Report for Research Project 985-RP, "Implementation of Thermal Storage in Building Mass," "There is inherent energy storage within a building, which can be used to change the time distribution of the equipment cooling loads and significantly reduce the cooling costs for a building."[4]

The base-loading concept of using the building mass as thermal storage is not new. "Braun [principal investigator] used dynamic optimization, applied to simulations, to determine optimal building control strategies and determined that energy costs could be reduced up to 50%, with greater savings being achieved with time of day rates. Similarly, he demonstrated that demand charges could be reduced by about 30%, with greater savings in buildings not occupied for the whole day.

"Braun proposed a combination of mechanical precooling and 'free' precooling to utilize the thermal mass potential of the building and stated that by precooling the building to five degrees below the comfort zone, both the demand and energy charges could be reduced effectively."[4]

Simmonds showed it was possible to use night ventilation purge to cool the building mass and reduce the refrigeration

system size and still maintain comfortable occupant spaces (this would be used only when the nighttime dew point is less than or equal to the desired indoor humidity level).[1]

Also from Olesen, et al., "A new trend, which started in the early nineties in Switzerland (Meierhans, 1993, 1996), is to use the thermal storage capacity of the concrete slabs between each storey in multi-storey buildings. Pipes carrying water for heating and cooling are embedded in the centre of the concrete slab."[2]

Thermal storage is not new to district energy. According to the 2004 *ASHRAE Handbook,* "Both hot and chilled water thermal storage can be implemented for district systems…. Depending on the plant design and loading, thermal storage can reduce chiller equipment requirements and lower operating costs. By shifting a part of the chilling load, chillers can be sized closer to the average load than the peak load. Shifting the entire refrigeration load to off peak requires the same (or slightly larger) chiller machine capacity, but removes the entire electric load from the peak period. Since many utilities offer lower rates during off peak periods, operating costs for electric-driven chillers can be substantially reduced."[3]

Figure 3: Building indirect connection for both heating and domestic hot water (substation).

The preceding text establishes the foundation for defining the benefits of using the building mass as the storage medium for both heating and cooling, and the design principle is based on the following statement from Olesen, et al., "As the heat transfer between the heated or cooled surfaces, the space and people in the space is mainly by radiation, it is important to use the operative temperature for specifying comfort conditions and for load calculations. With concrete slab systems, where the dynamic effects and thermal storage capacity of the slabs are used, the operative temperature should during the day ramp inside the comfort range. Studies by Knudsen (1989) show that as long as the temperature change is less than 5 K per hour the temperature range based on steady state conditions (ISO 7730) is still valid."[2] (See Standard 55-2004, which establishes operative range and allowable temperature drifts and ramps.)

So the principle becomes, "For a well designed building with a low heating and low cooling load, a concrete slab system may be controlled at a constant core (water) temperature year-round. If, for example, the core is kept at 72°F (22°C), the system will heat at room temperatures below 72°F (22°C) and cool when the room temperature increases above 72°F (22°C)."[3]

The heating and cooling flux limitation of an activated core is established by the building/mechanical thermal inertia characteristics for ceiling systems to be stable (avoiding uncontrolled heating and cooling) at a nominal 10 Btu/h·ft² (30 W/m²) based

on ideal fluid temperatures between 64°F (18°C) and 77°F (25°C). It is also important to distinguish the core conditioning capacity from those of a radiant floor system whose flux performance in the heating mode peaks around 32 Btu/ft² (100 W/m²) and 12 Btu/ft² (38 W/m²) for a cooling.

Olesen, Simmonds, et al., have noted, "A special case for floor cooling is when there is direct sun radiation on the floor. In this case the cooling capacity of the floor may exceed 100 W/m² (Borresen, 1994). This is also why floor cooling is increasingly used in spaces with large glass surfaces like airports,[5] atriums and entrance halls."
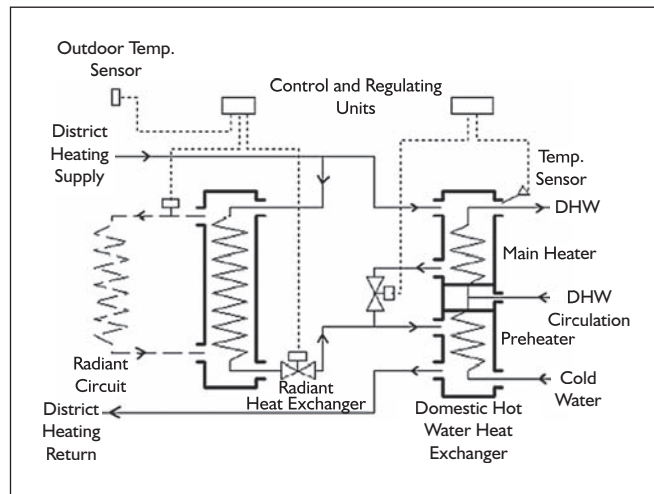
The heat exchange coefficients (convection + radiation) are listed in *Table 1*.

A summary of the benefits of activated core cooling (also applies to heating) principles from the ASHRAE Research Project 985-RP follows:

• "…thermal mass precooling helps reduce demand peaks and on-peak energy usage because the cooled mass has a greater availability to absorb heat gains to the conditioned space."

• "Operating the cooling plant at night may result in enhanced cooling equipment performance. The efficiency of the cooling plant is directly dependent on the operating temperature of the condenser and hence, operating the equipment at night, i.e., at lower operating temperatures, translates to improved cooling equipment performance."

• "Enhanced equipment efficiencies may be obtained by operating the cooling equipment at part loads. Shifting the loads causes the plant to operate at a lower part load ratio during the daytime periods, thus giving higher plant efficiencies for plants with favorable part load characteristics."

• Sensible cooling using embedded pipes can be assisted by "Nighttime ventilation cooling…(which) uses the air handler to feed in cold nighttime air (when the dew point is low enough) into the building to reduce the cooling loads for the subsequent day. In cases where the outdoor air temperature drops below the daytime setpoint, this may serve as a means for sensible cooling of the zone and reduce total cooling plant requirements."

Conditioning the building mass is best achieved by direct conduction of heating and cooling pipes embedded in the slab, and, by its nature, produces a by-product of an indoor radiant comfort conditioning system.

Radiant Heating and Cooling Systems

Practitioners and students of HVAC design are encouraged to review the details of Standard 55-2004 and consider that the human body transfers between 40% and 50% of its energy via

radiation. Many ASHRAE and other studies state comfort levels are highly influenced by floor/ceiling surface temperatures, temperature stratification, radiant asymmetry, and air velocities (draft). It is not logical to ignore the scientific benefits of radiant heating and cooling— not only from a physiological perspective but also from a controllability point of view.

Consider this: "…relative small temperature differences between the heated or cooled surface and the space are typical for surface heating and cooling systems. This results in a significant degree of self control, because a small change in this temperature difference will influence the heat transfer between the cooled or heated surface and the space significantly."[2]

This control stability is suitable for all regions and ideal for geographic regions, which experience extreme temperature and humidity swings since it's practical to use radiant for sensible base loading (core conditioning) and the ventilation system for peak temperature, and latent/humidity control.

Olesen provides this guidance, "The important factors for the heating and cooling capacity of hydronic systems embedded in concrete slabs are the heat exchange coefficient between the slab surface and the space, the acceptable minimum and maximum slab surface temperatures based on comfort and consideration of the dew point in the space and heat transfer between the pipes and the surface."

It is important to distinguish between the capacities obtained from core conditioning system and those of a radiant system.

Dedicated Outdoor Air Systems

By directly conditioning the building core temperature and, thus, addressing sensible base loads with radiant, the only remaining design conditions to consider are supplemental peak heating loads, latent cooling loads and ventilation requirements. All three can be handled with a dedicated outdoor air system (DOAS).

Dieckmann, Roth, Brodrick, provide a concise benefit explanation of using a combination of a sensible base systems and DOAS by saving energy in at least four ways.[7] "First, a DOAS reduces ventilation energy consumption by reducing the total ventilation airflow needed to meet Standard 62 ventilation re-

quirements. This is due to the inherent precision of the DOAS in delivering required ventilation flows in the aggregate and in the individual zones in the building.

"Second, reductions in the total ventilation airflow decrease the energy expended to *condition* the ventilation air during cooling and heating seasons. Simple analyses performed by TIAX suggest that a DOAS decreases total space heating energy consumption by approximately 10%.

"Third, because the ventilation makeup air is separately conditioned from the internal loads, with the entire building humidity load handled in the process…. This enables the use of higher chilled water temperatures for the internal (sensible) loads (approximately 55°F [13°C] evaporating temperature vs. 40°F to 45°F [4°C to 7°C], typically), increasing the COP of the air conditioner compressor.

Fourth, by decoupling temperature and humidity control, it creates an ideal situation for VAV, where the volume of conditioned airflow rate varies in proportion to the net cooling or heating load. This significantly reduces blower power during the large proportion of the year when full heating or cooling capacity is not required (or where activated core is used). Note that this applies to both chilled water based systems and to DX systems."[7]

By effectively managing indoor humidity levels, a DOAS also enables the application of energy-efficient radiant ceiling systems for sensible cooling, where water is used to transport cooling instead of air. The DOAS architecture readily incorporates energy recovery heat exchange between the makeup air and exhaust, reducing peak and seasonal cooling and heating loads needed to condition makeup air.[7]

"This approach allows each component of the HVAC system to do what it does best."[6]

As stated by Mumma, "The integrated panel-cooling/DOAS approach provides superior indoor air quality and thermal comfort, and that alone should be sufficient incentive for the industry to use the concept. This is especially true since the Lawrence Berkeley National Laboratory estimates that U.S. companies could save as much as $58 billion annually by preventing sick-building illnesses and could benefit from up to $200 billion in productivity increases each year."[8]
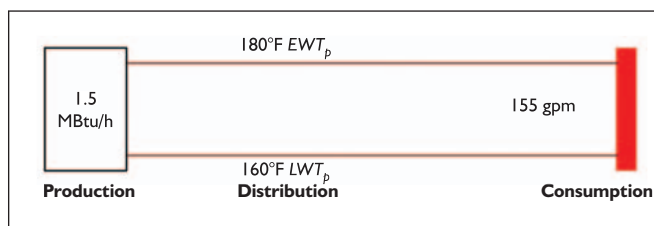

Figure 4: Traditional design principle. Simplified flow and temperature profile for direct connected high-temperature baseboard, radiator or fan/coil system.
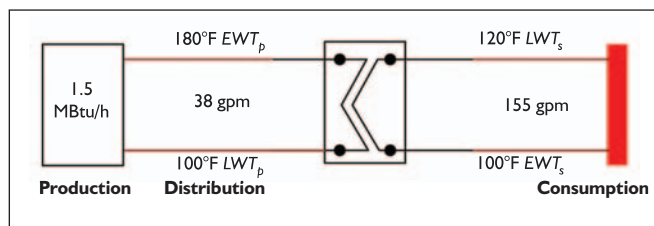

Figure 5: District energy principle. Simplified flow and temperature profile for indirect connected substation serving low-temperature radiant floor heating systems.

Mode	Heating		Cooling	
Surface	Btu/h·ft²·°F	W/m²·K	Btu/h·ft²·°F	W/m²·K
Floor	1.9	11	1.2	7
Wall	1.4	8	1.4	8
Ceiling	1.1	6	1.9	11

Table 1: Total heat exchange coefficient (convection + radiation) between surface and space for heating and cooling.[2,9]

Conclusions

Two dominant challenges influencing modern building space conditioning system design are energy costs and human comfort. One is driven by economic conditions and the other by the physical condition of an aging population. A review of ASHRAE research and documentation suggest the integration of the four common and proven systems identified here is a potential concept that could easily and simply solve both challenges while promoting the natural progression of green building habitation.

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