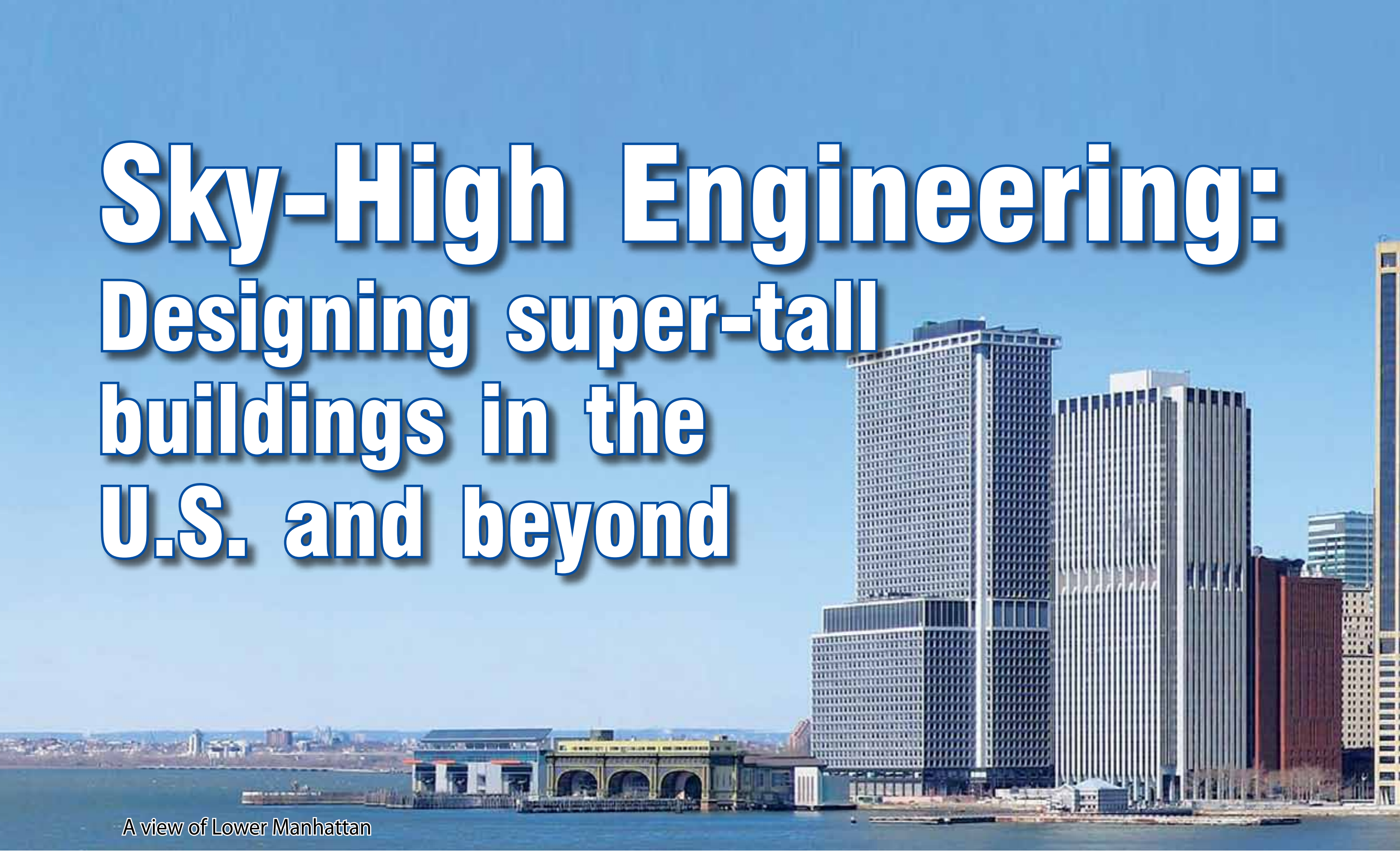
Sky-High Engineering:

Designing super-tall buildings in the U.S. and beyond



A view of Lower Manhattan

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Introduction

While the U.S. has traditionally held the keys to super-tall buildings and their design, tomorrow's super-talls are rising primarily in the Asian and Gulf regions as rapid economic growth catapults newly industrialized countries into the ranks of the developed world. Driven by the lack of undeveloped land in these urban areas, the aspiration to develop into a financial hub and the desire for national and cultural prestige, worldwide super-tall building development is on the rise.

By far the largest, and often times most overlooked, challenge to designing super-tall structures around the globe is understanding the local practices, culture and codes and standards that govern each region. For example, residents in South East Asia walk barefooted in their apartments year-round. During the winter months concrete floors would be too cold for this practice, so radiant heat flooring is commonly used. Designed in conjunction with the HVAC system, the radiant floor warms tiles by delivering hot water to a pipe sandwiched in the floor slab. Radiant floor tubing, however, is not designed to withstand a typical super-tall building hydronic system pressure of more than 400 lbs./sq. in., but instead, is limited to only 90psi of pressure. Therefore, a radiant floor system in a super-tall building located in South East Asia would require pressure breaks to be installed at various heights throughout the building.

Another challenge for super-tall building design is integrating sustainability. While designing energy-efficient systems will help minimize the additional operating costs that accompany mile-high floors, it can be more complicated than it appears. For one, extra attention must be paid to stand-by systems that can, for example, provide electricity for 100+ floors of egress systems in case of a power outage. Another might be examining an envelope that is used to daylight the building. Due to the height of the structure, both daylight and heat infiltration can affect lower and higher floors differently.

A key ingredient to any super-tall building design is an understanding of all HVAC design parameters and their influence on building height, while keeping local environmental considerations in mind. This white paper will examine the influence of the building's height on:

About the Author

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temperature, air pressure, wind speed, moisture, solar radiation, wind effect, stack effect, ventilation, the building envelope, noise control, the air distribution system, daylighting, on-site energy generation and water distribution.

HVAC Design Parameters and their Influence on Building Height

Sky-sourced environmental conditions will vary with height above sea level. Tall buildings will be influenced more by these variations than smaller high-rise buildings. For example, since weather conditions in the lower atmosphere are by no means constant or predictable and temperature inversions occur from time to time, care must be taken when applying the effects of varying weather conditions and building height to mechanical equipment sizing.

Editor's Note
Syska Hennessy Group is presently designing the HVAC systems for five super-tall buildings in South Korea, ranging from 107 - 151 stories high.

Appropriate designs for these measures may be realized in an energy model of the building, since all of the weather and atmospheric effects may be applied over the course of an entire year and not specifically on a peak design day. One should understand that the energy model tools do not automatically account for the different outdoor air condition on higher floors from the lower floors. Using international standards and guidelines developed by the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) in combination with local codes and cultural practices will help

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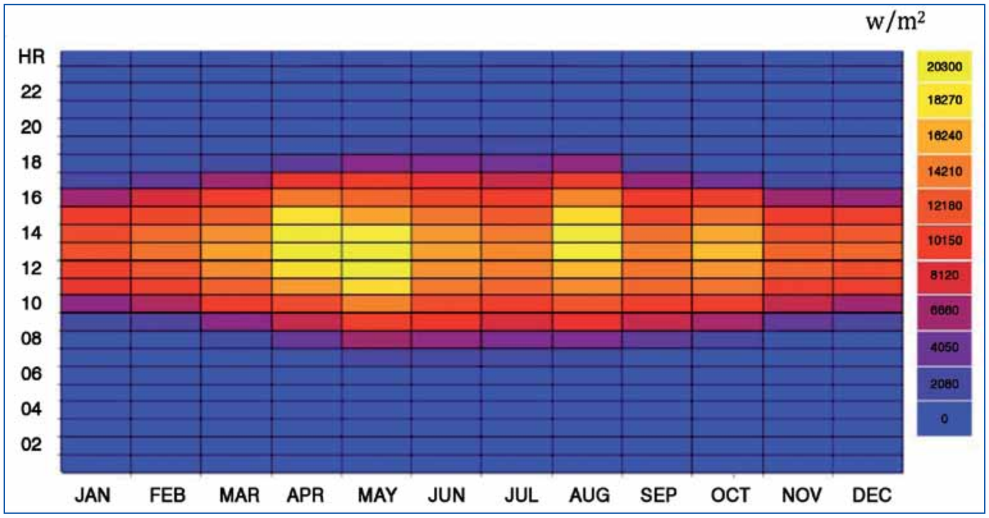

Figure 2: Incident solar radiation on horizontal surface - monthly total

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frame the design for each of the above measures.

Temperature

The outdoor temperature, for air at standard atmospheric conditions listed in the 2009 ASHRAE Fundamentals Handbook, may vary from 3.5° F to 3.6° F per 1,000 ft. (305m). When air is saturated with moisture, outside temperatures vary approximately 2.7° F per 1,000 ft. Best practice is to divide the building into zones to allow for different temperature and pressure requirements. Local temperature differentiations should be used in modeling the building's annual energy consumption. The following is an example for these reductions. See *Figure 1*.

Altitude ASL	Temp. Correction	Design DB	Moisture reduction Design WB
45 feet (13.7m)	0°F	95°F (35°C)	82°F (27.8°C)
500 feet (152.4m)	1.23°F (0.7°C)	93.77°F (34.3°C)	81.7° F (27.6 °C)
1000 feet (304.8m)	2.58°F (1.4°C)	92.47°F (33.6°C)	81.4°F (27.4°C)

Figure 1: Effect on outdoor conditions due to change in altitude

Air Pressure

Air pressure and air density decrease with elevation. Less energy is required to cool thinner outside air that is also at a lower temperature and moisture content. Fans may be selected for altitude correction, but it is not required by ASHRAE Standard 62.1 "Ventilation for Acceptable Indoor Air Quality." Volumetric flow rates are based on an air density of 0.075 lb/ft^3 of dry air at 70° F, which differs according to climate. For equipment sizing, use the corrected air condition based on elevation. Effects of decreased air pressure and density with building height may reduce the annual energy consumption of the building, which should be evaluated in the building's energy model during design.

Wind Speed

Wind speed and infiltration both increase with altitude. Wind speed will also increase the heat transfer of a building to the outside. This reduction may be applied in the energy model. Infiltration shall be considered at all levels of the building for both heating and cooling.

Airflow around the building may also affect the operation of the HVAC systems connected to exterior louvers. Based on preliminary calculations, exhaust fans at 500 ft. above sea level should include an additional 0.2 in. wg of pressure and for mechanical equipment rooms (MER) above this level, an additional 0.4 in. wg should be included.

Moisture

The moisture ratio can decrease with altitude depending on local dry bulb temperature and pressure. The pattern of moisture ratio decrease is similar to the ASHRAE dry bulb temperature drop profile. There can be a 20% to 40% reduction in moisture in the air at 1,000 meters above sea level. Moisture reduction with altitude can account for a summer cooling load reduction of as much as 4% at 500 meters (1,640 ft.) above sea level (See *Figure 1*).

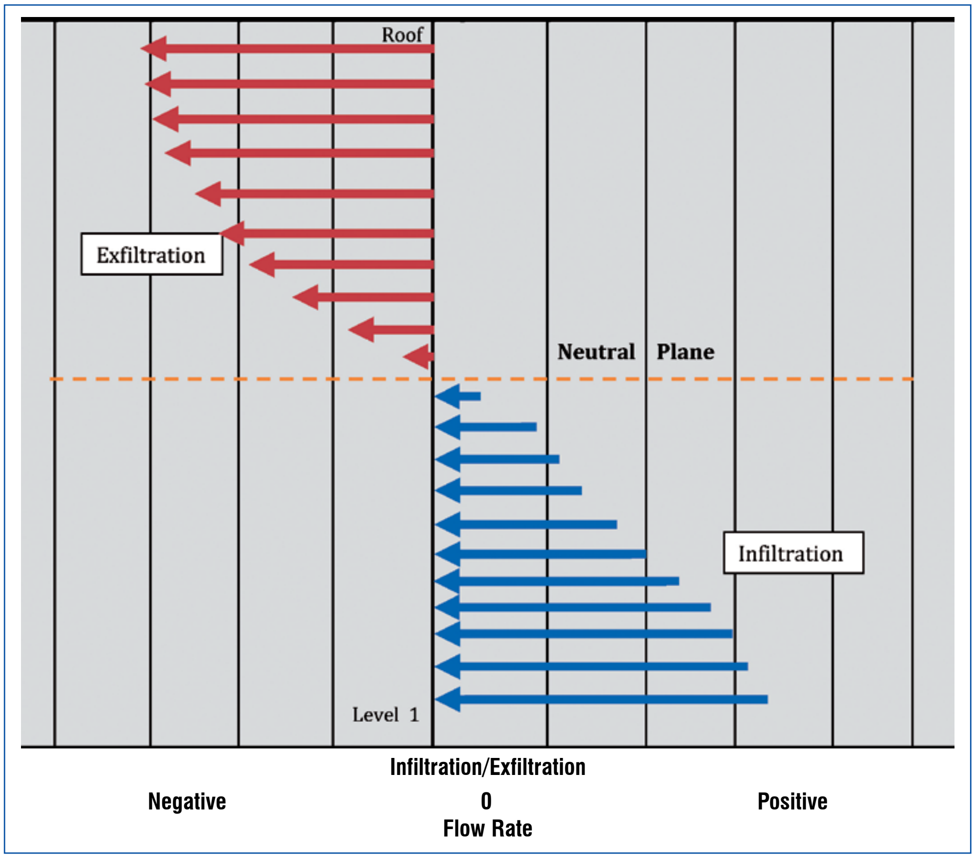

Figure 3: Heating condition: no wind or ventilation system influences during winter condition (it reverses during summer)

Solar Radiation

Direct and diffused solar radiation rises with altitude, with a 4% to 5% increase in UV radiation at 1,000 ft. (305 M). Diffused radiation from the ground is likely to decrease with altitude since there is a thicker air and moisture mass to travel through. In some areas, however, such as the east coast of the U.S., local atmospheric conditions and cloudy skies can cause a decrease in solar radiation with altitude. This measure is very site specific (See *Figure 2*).

Wind Effect

Airflow around a building may affect the operation of its HVAC systems. Wind pressure on air intakes and relief and exhaust louvers can have a significant effect on the mechanical systems serving the build-

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ing. Upwind openings will be under positive pressure and downwind openings will be under negative pressure. The higher in the building the louvers and equipment are located the more impact the wind pressure will have on the systems.

ASHRAE 2009 Fundamentals methodology can be used to calculate the effects of wind pressure on various mechanical systems throughout the building. Preliminary calculations will indicate wind assisted and wind opposed pressures expected in the range of ±0.3 to ±0.4 inches water gauge (75 PA to 100 PA). This is based on using the ASHRAE wind speed for the extreme annual design condition of 21.8 mph (9.75 m/s) to 23.2 mph (10.4 m/s). Wind speed will increase above the surface of the earth until it reaches the gradient winds, or the wind boundary layer. In super tall high-rise buildings, wind speeds need to be analyzed at various heights of the equipment rooms within the building. Fans should be selected to overcome increased static and opposing wind pressure and to maintain correct pressurization. They should be equipped with variable speed drives (VSD) and air flow monitors to assure that the correct amount of air is delivered to or exhausted from building spaces.

Stack Effect

Stack pressure or stack effect is the hydrostatic pressure in the building caused by the weight of a column of air located within. Gradients in the stack pressure over the height of the building during the different seasons can adversely affect occupant comfort, HVAC systems performance and the operation of elevator and building entrance doors.

The design team must address the stack effect issue within the super-tall building. Proportional to the temperature differential between the inside and outside of the building, stack pressure must account for different levels of building height (see Figure 3), as tall buildings will experience significant temperature stratifications indoors, especially during the winter months with pressures outward at the upper floors and pressures inward at the lower floors, both proportional to the distance from the building's neutral pressure level. Calculations for the stack pressure will include corrections for the air density gradient over the entire height of the building. Results from wind tunnel testing by the wind-engineering consultant must also be reviewed and analyzed by the architect, the elevator consultant, structural engineer and the MEP engineer to provide a unified solution to stack effect mitigation.

Architectural building features, such as vestibules with revolving doors, special gaskets for elevator and vestibule doors, vertical stairwell offsets as well as mechanical systems configuration and building management system (BMS) control measures must be studied to counter the effects of stack pressure within the building. The following are some of the suggested HVAC system enhancements to alleviate the stack effect:

- Monitor and control air balance systems to assure that correct amounts of outside and exhaust air are delivered to each space in response to building pressure. Interconnected systems will track one another to maintain pressure differentials.
- HVAC systems can keep the building slightly pressurized or neutral in reference to the outside of the building. This should be monitored and controlled at various heights throughout the building.
- HVAC equipment should be specified with VSDs that respond to a pressure-monitoring system at various heights.
- HVAC airside systems should be vertically segmented to avoid excessive pressure differentials between the bottom and top of the duct risers.

To minimize stack effect in the building, including at elevator shafts, the following strategy can be considered:

- The vertically stacked areas of the building can be divided into different riser segments by MER and/or elevator equipment rooms. The vertical shafts should be sealed at the floor and ceiling of the MERs, with penetrations through slabs containing duct and pipe sleeved openings or electrical conduit/bus ducts.
- Architectural separation should be considered at different levels (entrances, core areas, etc.).
- Vestibules can be utilized.
- Areas should be pressurized to minimize infiltration.
- Pressure monitoring control for each riser segment should be considered.
- Special seals at the entrance doors should be considered to reduce air leakage. The main entrance door to the building should consider revolving doors with a vestibule and a double entrance door to minimize infiltration and stack effect.

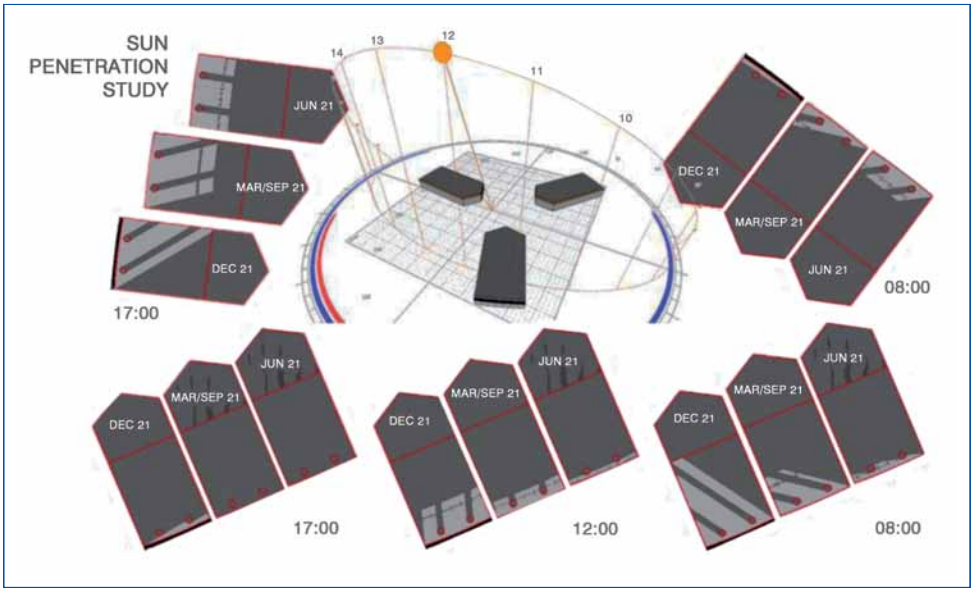

Figure 4: Annual solar impact on natural daylighting

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Ventilation

The ventilation requirement is very important for the super-tall buildings not only for human comfort, but also to overcome any leakage and infiltration through the exterior envelope. Depending on the local climate and wind velocity, air leakage can be expected to be in the range of 0.1 to 0.6 cfm per sq. ft. of unit curtain wall area at 0.3" of wg (75 pa).

The ventilation rate for human comfort in specific areas can be based on ASHRAE 62.1 guidelines, while special ventilation requirements for kitchen, toilets, laundry equipment, etc. should also be considered.

Noise

Depending on the local economy and market profitability, a developer will decide what type of tenants should be considered for the super-tall building. The current trend in many countries, including South Korea, is to develop a mixed-use facility, which includes offices, hotel, residence, retail and observation deck to generate revenue. In these facilities, special attention is required for noise control. Aspects to consider include: noise control between floors, noise transmission between adjacent residence and hotel guest rooms, outdoor noise penetrating occupied spaces through curtain walls and noise and vibration generated by exterior structure (like louvers) with wind. The ideal noise level for private spaces like offices, residential apartments and hotel rooms should be between NC-30 and NC-35.

Envelope

The building's exterior envelope is generally designed by the architects. However, it is very important for the MEP engineer to review and check the proposed envelope design to assure it complies with local energy codes. The glass SHGC Value, U-factor, visible transmittance, thermal break at the mullions and more will all have a major impact on the total heating and cooling load of the building.

In many countries, depending on the local climate, residents prefer operable windows in their apartments to take advantage of the natural ventilation in lieu of air conditioning. Large wind pressures and potential stack effect issues in super-tall buildings make operable windows impractical, since there is a possibility that the substantial wind velocity would blow windows open or closed. If natural ventilation is employed, however, it should be done with non-glass openings such as vented mullions that are operated by a knob or crank.

The envelope design should also consider natural daylighting for energy conservation and improved indoor light quality (See *Figure 4*). When properly controlled, this can help minimize the use of electric power for the lighting and reduce winter heating demands.

The use of operable shades on the building's envelope can reduce energy, as they can help control glare and daylight performance for the occupants and may be considered. The energy benefit of properly-designed shades in a multi-climate area can reduce incident energy transmission. The operable shades will provide the ability to modulate lighting conditions and may offer some winter heating benefits during early morning and late afternoon hours as well.

Daylighting

The most important components of any sustainable building short or tall are daylighting and controlling the electric lighting. Daylighting can provide significant energy savings and occupancy comfort when designed correctly. This includes the specification of continuous variable dimmers for the perimeter office spaces of a super-tall structure, resulting in a substantial reduction in both electrical and cooling energy, required and consumed. Designed in conjunction with the building's envelope, each system has its advantages and disadvantages and should be reviewed prior to selection.

Air Distribution System

The air distribution system for a super-tall building should be tailored to the climate it serves, addressing the operation of each area, including initial and operating costs as well as energy conservation. With rising energy rates and new LEED qualifications, sustainability plays a major role in the design of these systems. A Life Cycle Cost (LCC) analysis should be conducted prior to the selection of any system. The following are some options that can be considered for office spaces in super-tall buildings, depending on the tenant's leasing agreement:

Variable Air Volume System from Central Air Handling Units (AHU)

Variable Air Volume (VAV) systems provide air conditioning to the areas served via ceiling-mounted VAV boxes. VAV systems control the temperature in a space by varying the quantity of supply air rather than varying the supply air temperature. The Building Management System (BMS) should be designed to vary the supply air temperature to improve energy efficiency while maintaining thermal comfort.

Floor by Floor AHUs with Access to Louvers

This arrangement of equipment assumes that there will be a mechanical room on each floor to supply heating and cooling needs to each space. This system takes advantage of "free cooling" through the use of an airside economizer. In order to take advantage of "free cooling," the mechanical rooms will have to be placed on the perimeter of the building so that the louvers can regulate the amount of outside air brought into the mechanical room. VAV terminal units can be used in this configuration.

Fan Coil Units

Fan Coil Units typically consist of a fan, filter, cooling and heating coil and are typically located within the ceiling of the office space, re-circulating air that mixes with primary outdoor ventilation air. Fan coil units have cooling coil condensate pans that are piped to the sanitary drain system and often include secondary drains that are piped to locations where visible evidence of condensate blockage can be provided. The primary outdoor ventilation air is ducted from central air handling units located in central mechanical rooms to the fan coil units through vertical duct shafts and ceiling-mounted ductwork. Central air handling units and distribution ductwork are sized only for minimum outdoor ventilation air quantities.

Under Floor Air Distribution

The Under Floor Air Distribution (UFAD) system delivers conditioned air to occupied spaces via floor level air distribution devices. The system typically utilizes a raised floor to either provide a pathway for supply air ductwork, or often acts as the supply air plenum itself. The system is designed to maintain the space temperature in an occupied zone only. This provides diversity in the cooling load for the equipment mounted above the occupied zone. In this system, the air is supplied at the floor level. For the occupant's comfort the temperature of the supply air has to be warmer than the air distribution system from the ceiling. This allows more time for the airside economizer cycle to conserve energy. In this strategy, floor-to-floor heights may increase.

Variable Refrigerant Flow System

A Variable Refrigerant Flow system uses a split-type variable flow air conditioning unit, available in both an air conditioning and heat pump model, the latter can provide both heating and cooling. Refrigerant piping runs above the ceiling to a remote air-cooled condensing unit located in the exterior mechanical equipment room at each floor. The equipment requires a defrost cycle and therefore a separate perimeter heating system is recommended at lower outdoor air temperatures. A separate outdoor air supply system is required as well, as this is a re-circulating system.

On-Site Energy Generation

To overcome the high cost of energy, on-site energy generation can be considered for all super-tall structures when appropriate. A detailed investigation of the potential for on-site generation that assesses the feasibility of the project site, initial and operating costs and maintenance requirements is required. Here are some potential opportunities:

Cogeneration - Fuel Cell

A fuel cell is an electrochemical conversion device in which the energy of a chemical reaction is converted directly into electricity. Significant reduction in purchased electricity can be achieved by efficient on-site energy generation through Combined Heat and Power (CHP), generally referred to cogeneration. During this process, waste heat from the electrical production is used to heat the building. An augmentation to this strategy is often referred to as tri-generation, which uses an absorption chiller to provide cooling from the waste heat. Co-generation can be achieved not just with fuel cells but also with any on-site generation system that uses fuel to generate electricity and waste heat, such as gas turbine or gas engine.

Photovoltaic

Along with fuel cells, photovoltaic (PV) generation represents the greatest opportunity for on-site renewable energy integrated into the building site. Building Integrated photovoltaics (BIPV) are PV materials that are used to replace conventional building materials in parts of the building envelope such as the roof, skylights or facades. The advantage of integrated photovoltaics over more common non-integrated systems is that initial costs can be offset by reducing the amount of building materials that would normally be used in construction, replaced by BIPV modules. In addition, since BIPVs are an integral part of the design, they generally are more aesthetically appealing than other solar options. An LCC analysis of the replacement of BIPV's should be considered in the evaluation of their use.

Sea, River or Well Water Heat Recovery

A building's central plant is a major consumer of energy. Seawater, river and well water located adjacent to the property offers an attractive opportunity and can be used for central plant heat rejection. This approach would eliminate the need for cooling towers, which results in lower installation and operating costs.

Wind Energy

Wind power is the conversion of wind energy into a useful form, such as electricity, using wind turbines. Generally, wind turbines are not expected to provide building-scale power generation. Wind turbines can be installed to benefit from the natural airflow. This is a highly-visible element and an important technology for the future energy market.

Geothermal

Geothermal power, or the collection and rejection of absorbed heat derived from the underground heat sink to be used as energy. This requires no fuel, and is therefore virtually emissions-free and insusceptible to fluctuations in fuel cost. Because a geothermal power station doesn't rely on transient sources of energy, unlike, for example, wind turbines or solar panels, its capacity factor can be quite large. However, the amount of land required for a geothermal system is significant.

Solar Thermal Energy

Solar Thermal Energy (STE) is a technology used to harness solar energy for thermal energy (heat). The U.S. Energy Information Administration (EIA) defines solar thermal collectors as low, medium or high-temperature collectors. Low-temperature collectors are flat plates generally used to heat swimming pools. Medium-temperature collectors are also flat plates, but are used for creating hot water for residential and commercial use. High-temperature collectors concentrate sunlight using mirrors or lenses and are generally used for electric power production. STE is different from photovoltaics, which convert solar energy directly

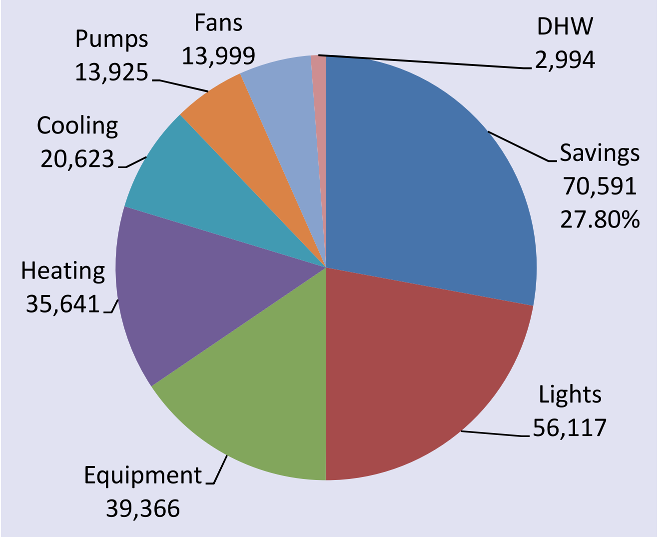

Figure 5: Annual site energy use in HVAC systems - showing % site energy savings (millions BTUs)

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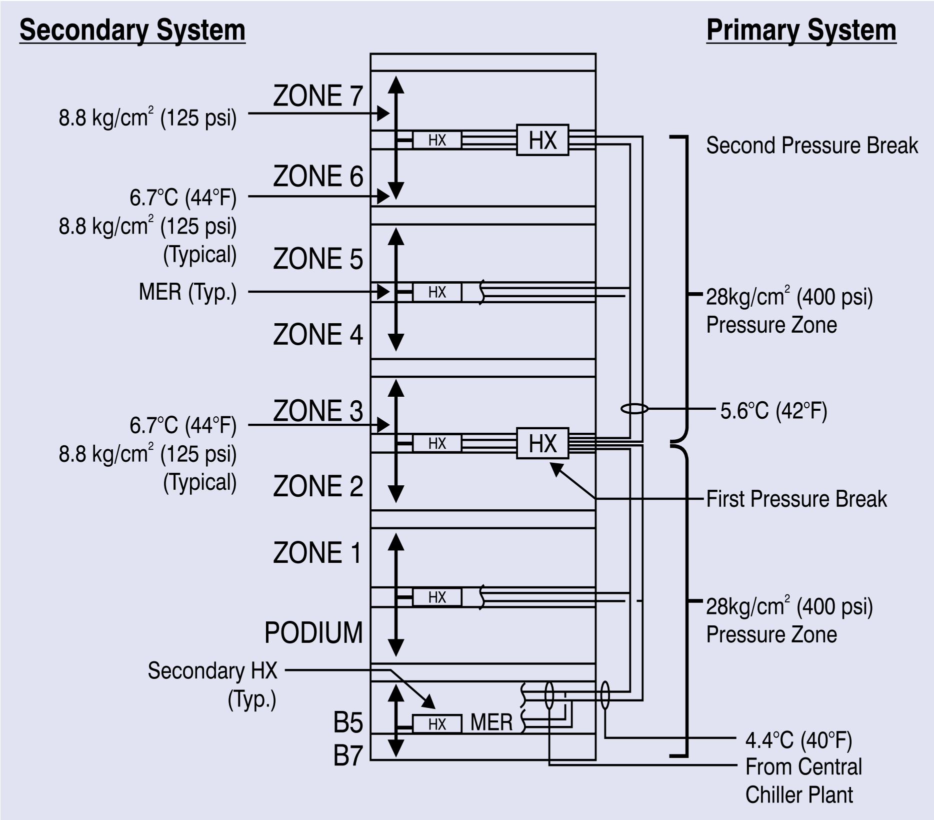

Figure 6: Chilled water pressure breaks. Hot water pressure breaks will be similar

into electricity.

Detailed energy modeling and simulation should be considered prior to implementation of any of the above methods for a better understanding of building load and system selection (See *Figure 5*). To evaluate indoor air flow and circulation patterns, conduct air flow modeling to identify interior spaces to assess the ventilation performance and air temperature distribution and velocity profiles.

Water Distribution

Water distribution requires proper attention in super-tall buildings, the distribution of which entails both cooling and heating plants. For a chiller plant, the type of chillers used must provide reliability, flexibility and best utilization of available energy sources. The chillers are characterized by energy source (electricity, steam or gas), chiller type (centrifugal or absorption) and refrigerant type. Centrifugal chillers are available with refrigerant HCFC-123 and HFC-134a. (Refrigerant HFC-134a currently has no phase-out schedule.) Absorption chillers do not use HFC- or HCFC-based refrigerants. Instead, absorption chillers utilize lithium bromide solution mixed with water as the refrigerant.

The local code requirements should be considered in the selection of chillers. For example, South Korea code requires the use of electric chillers not to exceed 40% of the chiller plant capacity. The following technically feasible chiller alternatives for the central chiller plant can be considered: Electric Centrifugal Chillers, Steam Turbine Driven Centrifugal Chillers, Gas Engine-Driven Centrifugal Chillers, Two-Stage Steam Absorption Chillers, Single-Stage Absorption Chillers and Direct-Fired Absorption Chillers.

Chiller Plant

For super-tall buildings to provide chilled water service to 100 or more floors, several thermal/pressure interfaces are required. Each heat exchange interface will result in a degradation of the chilled water supply temperature. Centrifugal chillers can produce chilled water at colder temperatures than absorption chillers, therefore, a proper selection of chillers should be utilized to maintain the supply water temperature serving the building. Each chiller plant should include a redundant chiller thereby providing enhanced system reliability.

Chilled Water Distribution

Chilled water can be circulated through the chillers and building zones using variable-flow pumping. Plate and frame-type heat exchangers are used as the thermal/pressure interface between the various zones of the tower (See figure 6). Each chilled water pipe loop should include a redundant chilled water pump.

Condenser Water Distribution

The chillers shall be connected directly to a closed loop condenser water system sized to accommodate the heat rejection in the associated chiller plant.

Waterside Economizer System

Plate and frame type heat exchangers can be provided in each chiller plant for free cooling when condenser water temperature conditions are favorable. Chilled water can be produced directly from the condenser water via heat exchangers. During this mode, the chillers will not be in operation.

Thermal Energy Storage System

An ice-based thermal energy storage system, providing peak-shaving cooling capacity, could be considered for the chiller plants. Ice produced in storage tanks is charged via a dedicated ice-making chiller and a glycol-circulating loop. Condenser water for the ice-making chiller can be supplied from the main condenser water system. The glycol-circulating pump can be provided with a variable frequency drive controller, so that it can operate during both tank charging and discharging modes. The ice-storage tanks are discharged by circulating the glycol solution through the tanks and a plate and frame type heat exchanger in the primary chilled water system. A dedicated primary chilled water pump circulates chilled water through the heat exchanger. Three-way diverting valves and temperature control valves in the glycol loop align and control the system for tank charging and discharging modes of operation.

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Typically, thermal energy storage systems are utilized when electric rates are lower at night in off-peak conditions. Based on previous experience, payback will be in the range of 15 to 20 years. The thermal storage system will also require significant floor space. It is recommended that an LLC analysis for the thermal energy storage system be performed.

Heating Plant

The heating plant will be sized to serve the heating loads of building components, as well as the domestic hot water heating equipment and winterization for the cooling towers.

Boiler Plant

As per South Korean regulation, chilled water plants must be configured so that at least 60% of the plant capacity is from non-electric sources, while the boiler plants must be capable of providing the non-electric energy source for this portion of the hybrid chiller plant.

Several technically feasible alternatives for new central boiler plants can be considered. The type of boilers used in the plant must provide reliability, flexibility and be capable of satisfactorily serving the space heating, domestic hot water and cooling needs of the building. Packaged boilers currently available on the market provide two basic types of heating: hot water and steam. Depending on the requirements, the following boilers can be considered: Hot Water Boilers, Low-Pressure Steam Boilers and High-Pressure Steam Boilers.

The hot water distribution system of super-tall buildings will be similar to those described for the chilled water system. The steam distribution can directly supply the AHUs using the pressure reducing valve station at each MER.

Economizers

Economizers can be provided in each boiler plant to recover heat from the flue gas stream. The heat recovered via the economizer will be used to heat the boiler feed water system.

Conclusion

The future of super-tall building design will likely be driven largely by the economics of the international real estate market, as it is today. While super-tall structures in Asia and the Gulf are typically multi-use, accommodating residential, retail, office and hotel space all under one roof, their U.S. counterparts have traditionally housed mostly commercial office space. Looking toward the future, however, U.S. super-talls will shift toward the international model to provide owners with flexibility in today's ever-changing and volatile real estate market.

Sustainability will continue to play a pivotal role in the design as well, as the drive toward carbon-neutral facilities continues with renewable technologies including solar, thermal, wind and geo-thermal integrated to minimize energy expenditure. Cultural norms and local codes and standards will also continue to diversify the super-tall building industry, as new technologies expand the opportunities to take 100+ floors to new heights. ◆