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HVAC Systems for Hyper-Efficient Buildings

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Over the last few years, a new variation on building energy performance standards, stressing building envelope performance, has begun to gain traction in the U.S. building marketplace. Originating in Europe, but, tracing its roots to the super-insulated house movement of the 1970s in the U.S. and Canada, the new standards have very specific requirements with respect to building envelope construction and performance with few specific requirements and mostly implied performance specifications for HVAC systems.

While the standard was originally intended for single family and attached dwellings, it has recently been applied to high rise residential and small commercial buildings. Buildings designed to these standards have sometimes been termed "hyper-efficient" in that the required calculated source energy use intensity (EUI), is far below that of conventional buildings and is comparable to the net zero ready building classification. This article will discuss the implications for HVAC design of the two most popular standards for hyper-efficient buildings, one from the Passivhaus Institut (PHI) in Germany, and one from the Passive House Institute US (PHIUS). While these two standards have some differences, their requirements are very similar and they have very similar implications for the HVAC designer attempting to accommodate buildings that aspire to comply with these standards.

Introduction

The two standards mentioned above, the PHI certification as a "Quality Approved Passive House"[1] and the PHIUS + Certification[2] program require unprecedented levels of performance for the building envelope. These requirements are specified in several ways, including a limitation on the annual heating and cooling demand, and/or a limitation on peak heating and cooling load, a requirement for airtightness (measured at a specified pressure differential by either by an air-change limitation or a flow rate per unit area of envelope), a requirement for heat recovery (HRV) or energy recovery (ERV) ventilation, with specifications for maximum fan energy and minimum efficiency and a limitation in the annual EUI of the building. Each of the standards also has a particular protocol for verifying the performance of the energy or heat recovery devices. The PHI standard also includes a limitation on the maximum difference between indoor air dry-bulb temperature and surface temperature of the building envelope.

While the design of HVAC systems to complement these building envelope oriented standards might seem to require only the accommodation the load reductions entailed by a high performance façade, other considerations come into play. Failing to recognize these complications can lead to significant problems with humidity control and part-load operation.

Specific HVAC Requirements of the Standards

The primary mechanism for compliance with these standards is through a peak load and energy consumption calculation using proprietary methodologies, supplemented with on-site inspections to verify a number of as-built conditions. The two versions of the Passive House

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standards have minimal specific requirements for HVAC, primarily oriented toward ventilation. The standards require a forced ventilation and exhaust system balanced to within 10%, with energy recovery or heat recovery units certified according to procedures published by the organizations.[3,4] The requirement for energy or heat recovery may actually be counterproductive in moderate climates, because the conditioning savings for outdoor air may be outweighed by additional fan energy for the pressure drop through the recovery device.

The requirement for "balanced" ventilation typically means using constant exhaust for kitchen and bathrooms and excluding certain variable exhaust appliances such as clothes dryers from the comfort envelope or providing makeup air by some other means, such as a direct outdoor air makeup connection for the dryer. The annual energy consumption limits, expressed as site or primary energy, dictate a highly efficient heating, cooling and ventilation system, even though there are few specific systems requirements. The ventilation rates assumed in the standards, typically 0.3 air changes per hour, are significantly lower than those required by the relevant ASHRAE standards. The PHIUS standard also has a comprehensive checklist that includes numerous site observations and measurements by a certified "rater" and the HVAC contractor that resemble a commissioning script. In summary, the stated HVAC requirements of the standards are as follows:

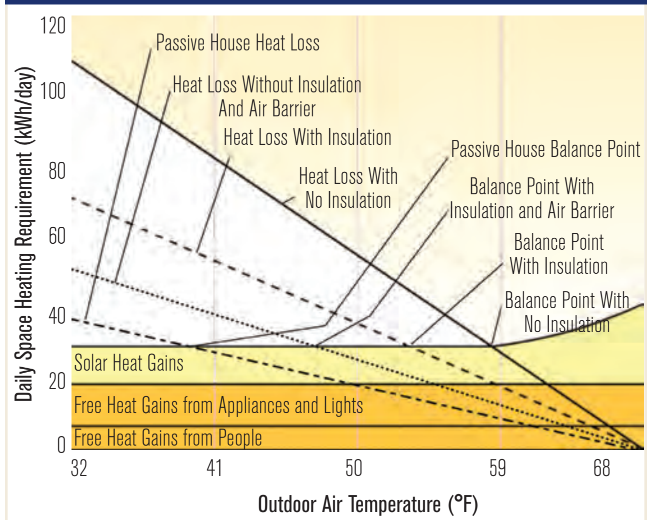
- Sufficient energy efficiency to enable the building to meet the calculated annual energy consumption requirement;
- Balanced ventilation system (supply/exhaust) using energy or heat recovery unit with a certified minimum recovery efficiency and fan energy limit; and
- Compliance with a number of specific detailed requirements listed in the checklist.

Despite this minimal list of specific requirements, the reality of providing comfort conditioning in a building with a very high performance envelope and very low internal heat gains introduces a new level of complexity to HVAC system design for the project.

Heating and Cooling Loads in a Hyper-Efficient Building

The extremely high performance building envelope required for this building type results in very low heating loads, despite the very low user equipment power density implied by the EUI limitation. An important characteristic of the resulting load profile is a very low balance point temperature, defined as the outdoor ambient dry bulb temperature at which heat losses through the envelope balance internal and solar heat gains. Reduced infiltration is a significant contributor to this load reduction. It is mandated in the standard through various specifications of air barriers and required architectural details, and requires on-site verification through blower doors or other means. *Figure 1* provides a qualitative illustration of relative values of balance point temperature for different levels of building envelope performance.

FIGURE 1 Heating requirements for different envelope performance levels as a function of outdoor temperature.



The upshot of the low balance point temperature is the need to exploit available free cooling opportunities whenever exterior conditions permit to avoid excessive cooling energy consumption. In residential applications, operable windows might suffice, but for other types of applications, airside economizer is almost mandatory. Obviously, for a building seeking certification under one of the standards, the ERV/HRV requirement is counterproductive for the provision of free-cooling during certain exterior conditions. HRV and ERV devices with controllable recovery capabilities, either in the form of supply air bypass or speed control for wheel-type heat exchangers enable the ventilation system to provide free cooling when it is needed.

Humidity Control in Hyper-Efficient Buildings in Cooling Mode

The limitations on peak heating and cooling loads in the buildings required by these standards are primarily achieved by reducing the sensible loads in the building, through high performance building envelopes, with low window wall ratios, infiltration control, and high performance glazing, and through drastically reduced equipment and lighting power densities. While latent loads in the cooling season will be significantly reduced by the increased airtightness of the building envelope, interior latent loads will not experience the same level of reduction. As a result, the sensible heat ratio (SHR), the ratio of sensible cooling load to total cooling load, during design conditions can be quite low, resulting in unacceptably high indoor relative humidity. The ventilation systems serving residential occupancies, furthermore, often deliver the tempered outdoor air directly to the space, so that residual humidity in the ventilation air becomes a space latent load. The impact of ventilation rates and energy recovery strategies were studied using a 1,000 ft^2 (92.9 m^2) apartment with two bedrooms (three occupants), two baths and a single kitchen. The building envelope is assumed to meet PHI requirements.

The PHI ventilation rate is 0.3 air changes per hour, while the ASHRAE ventilation rates depend upon whether one uses ASHRAE Standard 62.1-2016[5] or 62.2-2016.[6] Standard 62.1-2016 requires 0.06 cfm/ft^2 (0.65 L/s·m^2) and 5 cfm (2.4 L/s) per person for ventilation, for a total of 75 cfm (35.4 L/s) for the subject apartment, but requires 25 cfm (11.8 L/s) of continuous exhaust for each bathroom and 50 cfm (23.6 L/s) of continuous exhaust for each kitchen for a total of 100 cfm (47.2 L/s) for the two bathroom, single kitchen apartment, effectively 0.71 air changes per hour. ASHRAE 62.2-2016 requires .03 cfm/ft2 and 7.5 cfm/person, but the continuous exhaust requirements (20 cfm/bathroom (9.4 L/s) and 5 air changes per hour for the kitchen), result in 107 cfm (50.5 L/s). This study assumed 100 cfm (47.2 L/s) of exhaust and makeup air according to Standard 62.1-2016.

With an energy recovery device, the residual humidity in the ventilation stream is minimized, but still results in some additional elevation of the room dew-point temperature. The impact of this latent load can be very significant if the recovery device has only sensible capacity. *Table 1* shows space conditions resulting from different ventilation protocols in a typical apartment for 1% Design Conditions in New York City, 89.3°F DBT, 73°F WBT (31.8°C DBT, 22.8°C WBT). Total cooling load, both sensible and latent is limited to 4500 Btu/hr (1.3kW) per the PHI standard. Space conditions are calculated for non-conditioning heat recovery ventilators, energy recovery ventilators and conditioning dedicated outdoor air systems (DOAS) with either heat recovery or energy recovery components at both PHI and ASHRAE ventilation rates.

TABLE 1 New York City space conditions with different ventilation delivery strategies.

	SHR	SPACE DBT	SPACE RH
ASHRAE VENT RATE HRV	47%	76°F	68%
PHI VENT RATE HRV	66%	76°F	58%
ASHRAE VENT RATE ERV	71%	76°F	54%
PHI VENT RATE ERV	76%	76°F	52%
ASHRAE VENT DOAS HRV	66%	76°F	58%
ASHRAE VENT DOAS ERV	75%	76°F	53%

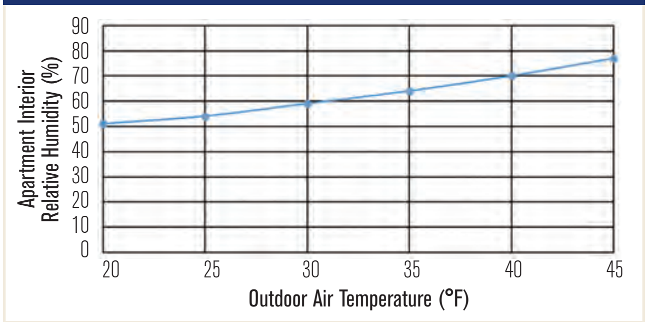
One can see from the resulting space conditions the impact of excessive humidity in the ventilation air in a humid climate. The reason that the selection of an HRV continues to have negative impacts on the space relative humidity when used in conjunction with DOAS is that the DOAS cooling load is included in the total space cooling load limitation. As a result, the increased total load on the DOAS caused by substituting an HRV for the ERV requires a reduction in the space load to offset. Since this space load reduction is almost certain to be sensible, it results in a decreased sensible heat ratio, resulting in an increased space humidity ratio for a given coil leaving condition and space dry-bulb temperature. While this result may be seen as an artifact of the two Passive House standards, it demonstrates the negative impact of the HRV in humid climates for reaching any particular peak load or EUI goal.

Humidity Control in Hyper-Efficient Buildings in Heating Mode

Changeover from cooling to heating operation does not alleviate humidity control problems if the building uses an ERV. Latent recovery for certified devices can be extremely high, often exceeding 80%, such that the exhaust stream from the building is limited in its ability to purge moisture vapor from the building. Combined with the extremely low infiltration rate resulting from the airtight envelope, moisture vapor generated in the space can result in an unacceptably high relative humidity in the space. Even with the stringent requirements for window and door thermal performance and the emphasis on correct wall configuration with respect to performance and location of vapor barriers, condensation could become a problem. *Figure 2* shows the space relative humidity at various outdoor air dew-point temperature points for the same 1,000 ft^2 (92.9 m^2) apartment discussed earlier. Total internal latent load for the space is 0.96 lbs/hr (0.44 kg/hr) from 3 persons, one 15-minute shower and 0.2 lbs/hr (0.09 kg/hr) miscellaneous latent loads. The space is maintained at 70°F (21.1°C). The ERV is assumed to have an efficiency of 80%. Total ventilation air meets the ASHRAE Standard 62.1 exhaust requirements.

The obvious solution for the excessive humidity issue is to disable energy recovery when outdoor air dew-point temperature is too high. The energy penalty for disabling recovery is likely to be minimal, since the balance point temperature of the building is so low, and free cooling will be beneficial during most of the hours that the exterior dew-point temperature is problematically high.

FIGURE 2 Space relative humidity as a function of outdoor dew-point temperature.



Terminal Sizing and Location

In a hyper-efficient building, space heating and cooling loads can be reduced to the point that the HVAC terminals, available in the market, are too large for the required service. The word terminal, in this case is used to refer to any single thermostat space conditioning device, ranging from the refrigerant fan coil of a multi-split VRF system, to a whole house furnace to a single package ground source heat pump. In many circumstances, consolidating multiple rooms into a single zone may not be advisable, due to different load profiles for the various rooms. Locating the thermostat in one room may result in discomfort in other rooms in the zone, if they have an incompatible load profile. Using an oversized terminal may not be an acceptable alternative, if consistent cooling loads below the minimum part load of the terminal result in cycling, diminishing the terminal's ability to provide adequate dehumidification. The ventilation system must be designed such that even when conditioning is not required, ventilation is continuous. The extreme airtightness of the building envelope eliminates uncontrolled ventilation as a source for fresh air within the building. Furthermore, low loads, which demand relatively low conditioning airflow per unit area may create difficulty in achieving uniform distribution of ventilation air and maintaining uniform conditions through the space. In a hyper-efficient building, distribution system design can be critical, even though total loads are reduced.

Terminal location, however, is not as critical as in a conventional building. The extremely high envelope performance significantly reduces the intensity of the peak perimeter heating and cooling loads, allowing terminals to treat an entire room, rather than concentrate on the perimeter portion of the room. For commercial buildings, reduction in intensity of the perimeter loads may allow simplification of the HVAC system and controls, eliminating the need for simultaneous heating and cooling within the same building.

Conclusion

Despite the exemplary energy efficiency of hyper-efficient buildings designed to the Passive House standards or seeking to achieve the very low EUI levels associated with net zero buildings, HVAC system design issues are not diminished. The issues that arise are often different than design issues with conventional buildings. Even though loads are greatly reduced, the HVAC system must accurately meet those loads and must be able to provide dehumidification even while sensible cooling loads are minimal. Below are some guidelines for designing HVAC systems for these buildings.

Configure ventilation systems to be compliant with the relevant version of ASHRAE Standard 62.1, even though some of the standards assume a much lower ventilation rate. While higher ventilation rates may make EUI and peak load limits more challenging, conforming with prevailing design standards reduces liability exposure.

Use a certified energy recovery ventilator compliant with the standard for which the building is seeking certification. The ventilator should be provided with some means of disabling recovery during appropriate weather conditions. The disabling mechanism may be in the form of a bypass for plate type heat exchangers, or motor control for wheel type exchangers.

Control the energy recovery device to maximize energy efficiency and indoor comfort. Disable energy recovery whenever outdoor conditions can reduce the cooling load required to maintain comfort settings. Disable the recovery device whenever, the outdoor air dew point is less than the indoor air dew point and space relative humidity is higher than desired.

Use a DOAS to separate ventilation conditioning from space conditioning, but ensure that ventilation air can be delivered to the space even when the space requires no comfort conditioning.

Design space zoning to be consistent with available terminal sizes, but be careful of consolidating spaces with conflicting behavior into a single thermostatic control zone. Pay particular attention to dehumidification during periods of low space sensible loads.

Maximized envelope performance is an important component of maximized building energy efficiency. The thermal behavior of spaces within those high performing envelopes, however, may differ significantly from that of spaces with conventional envelope performance. For the HVAC designer of systems to condition theses spaces, understanding of how these spaces behave is a necessity to efficiently maintain comfort within the space. The issues raised in this article are not intended to be comprehensive nor universally relevant. Clearly issues in arid climates are significantly different. However, this article aims to demonstrate the level of analysis required to design systems for these hyper-efficient buildings.

References

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5. ASHRAE Standard 62.1-2016, *Ventilation for Acceptable Indoor Air Quality,* p 20.
6. ASHRAE Standard 62.2-2016, *Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings,* p. 7. ■