Part-Load Control
Strategies for Packaged
Rooftop Units

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Introduction

When selecting packaged rooftop equipment, most designers size the unit to handle the total building cooling and heating loads at design weather conditions.

According to ASHRAE – American Society of Heating, Refrigerating and Air-Conditioning Engineers, design conditions (primarily dry bulb temperature) occur from 2.5 to 5% of the time throughout the year.

One method commonly used to illustrate the range of design temperature conditions over the entire year is the **bin hour profile**. A “bin” is simply a five-degree range of temperatures, along with the number of hours of occurrence between summer and winter design temperatures. When shown graphically a bin hour profile shows that most operating hours throughout the year occur at off-peak temperatures.

![Figure 1](image)

Figure 1 is a bin hour profile for Charlotte, North Carolina. As you can tell from the graph, during most hours of the year the dry bulb temperature is between 45 and 75 degrees F. Although the summer design temperature is 95°F and the winter design temperature is 15°F, these temperatures occur very few hours each year. This is why a part load analysis should be performed to predict the interaction between the heating and cooling equipment and the building load.

Although a bin hour profile is useful to analyze dry bulb temperatures it should be pointed out that at each dry bulb condition, there is also a mean coincident wet bulb temperature, which represents the average wet bulb temperature at that dry bulb. In many humid parts of the country, especially in applications with high quantities of outside air, the design wet bulb temperature may dictate the design operating condition for the unit. This is one reason that ASHRAE now lists a table indicating design wet bulb and mean coincident dry bulb.

Regardless which design temperature is used, dry bulb or wet bulb, a packaged rooftop unit must be capable of maintaining the desired building temperature and humidity levels. This is the easy part for rooftop equipment.

As mentioned above, the design dry bulb conditions occur at less than 5% of the cooling hours available. At ambient temperatures below design conditions, the building load is decreasing, while the full-load capacity of the rooftop equipment is actually increasing. This is illustrated in Figure 2.
This represents a challenge in controlling the packaged rooftop equipment to maintain comfort levels within the space. Buildings with oversized equipment tend to be cold and clammy as the air conditioning systems tend to have wide on and off cycles. During the on cycle, these systems tend to blast large volumes of very cold air which satisfy thermostats quickly and cycle the units off. During the off cycles, the inactive cooling coil is performing no de-humidification and the space becomes uncomfortably humid. In fact, during off cycles re-humidification occurs as untreated moist ventilation air is introduced to the space. Also, the residual water on the indoor coil re-evaporates into the untreated air stream during the off cycles. At temperatures below design conditions, most equipment has excess capacity, so this re-humidification becomes a real comfort and IAQ issue.

This white paper will discuss how to properly apply packaged rooftop units to achieve the delicate balance between selecting a packaged rooftop unit that can handle the peak design cooling load and also maintain control of indoor comfort during the non-peak times of the year.

**Equipment Sizing**

First and foremost, the units should be sized properly. This means performing an accurate cooling load analysis and resisting the temptation to throw in ultra-conservative safety factors resulting in oversized units. This only serves to further the problems stated above. If a safety factor is applied during the load estimate calculation and then the next larger unit is selected, in effect the system will be grossly oversized.

Indoor relative humidities in excess of 60% have been attributed to the creation of IAQ – Indoor Air Quality problems such as “Sick Building Syndrome” since microorganisms thrive in humid conditions. In addition to causing short cycling of the equipment and humid conditions in the space, oversized equipment results in undesirable noise levels as well as drafts and ultimately creates higher installed and operating expenses for the building owner or tenants.

There are several easy to use load estimating software programs available for calculating building loads and sizing the HVAC equipment. These have proven to be valuable tools for the designer in terms of both accuracy and saving time. Once the design loads have been calculated, equipment selection and layout tasks are performed.

**Zoning Considerations**

Buildings may be served by a single large rooftop air conditioner or a large quantity of smaller units may be selected to provide individual control of specific areas (zones) within the building envelope. Factors that dictate how many units to use include:

- Economics
- Available Space
System Types and Controls

Constant Volume Systems

The simplest rooftop system is a constant volume system serving a single zone. Zones may vary in size from as small as 500 square feet to over 50,000 square feet. Constant volume means the supply airflow quantity (CFM) of the rooftop unit is constant at all times.

Typical control of a constant volume unit is achieved by using a single thermostat. The thermostat turns the unit on when heating or cooling is required and off when the space is within one or two degrees of the desired set point. Often these packaged rooftop units have at least two stages of cooling so that at part load, only a portion of the units’ cooling capacity is energized. This prevents excessive on-off cycling and wide swings in indoor temperature and humidity from occurring as the unit attempts to match its capacity to the building load. Two stage cooling is often accomplished by having two independent refrigerant circuits within the rooftop unit.

Another factor, which helps reduce the capacity of the unit, is the reduction in compressor capacity as the building load becomes satisfied. As the building cools down, the return air temperature to the unit’s evaporator coil drops causing the refrigerant temperature and pressure to drop accordingly. As the refrigerant pressure decreases, its density will also decrease, causing the compressors to circulate a smaller amount (mass flow) of refrigerant through the system. This reduction in unit capacity creates a situation whereby the unit capacity somewhat balances itself with the building load.

Some large packaged rooftop units utilize multiple compressors on each refrigerant circuit, which then allows more than the two stages of capacity control mentioned above. These systems must utilize control schemes or thermostatic control, which will allow for the multi-staging of the compressors. For example, a unit may have two independent refrigeration circuits with two compressors on each circuit. Since most commercial thermostats have two-stages of control, the unit will need an alternate method, sometimes called a “controller”, to cycle these compressors to obtain the four stages of capacity available. Units may utilize an integrated controller, which communicates with a space sensor in lieu of a wall-mounted thermostat. To prevent rapid cycling of these compressors, a time delay is often built into the control, which ensures at least five minutes elapses between on-off cycles.

Another capacity control device used on constant volume units is a suction pressure unloader. This type of control is used on semi-hermetic compressors and actually prevents refrigerant gas from entering compressor cylinders when suction pressure drops, signifying low building loads. These unloaders need no external controls and automatically attempt to match the rooftop unit’s capacity to the building load. Other benefits of this type of control include less compressor cycling and the ability to use standard two-stage thermostats to control the rooftop unit. (This may result in considerable dollar savings as off the shelf thermostats are typically much less expensive than step controllers.) Each stage of the thermostat controls a refrigerant circuit on the unit. Using suction pressure unloaders may allow the constant volume unit to have up to six or more capacity stages, thus improving temperature and humidity control as the rooftop unit capacity more closely matches the building load without excessive on-off cycling.
Variable Airflow with Constant Volume Rooftops (VVT Systems)

The next type of system we’ll discuss also uses constant volume rooftop units, but varies the quantity of air to multiple zones served. A control zone is an area within the building served by a single thermostat.

A constant volume rooftop unit can serve multiple zones by using a monitor thermostat along with individual zone thermostats located in each zone. This system is shown in Figure 3.

**Figure 3**

The monitor thermostat is the central traffic controller of the system. The monitor thermostat “polls” all of the zone thermostats to detect if there is a call for cooling or heating. If there is a pre-determined number of zone thermostats calling for cooling, the monitor thermostat will send a signal to start the rooftop unit and supply conditioned air to each zone. A zone thermostat is located in each control zone and is connected to a modulating zone damper, which is located in the branch duct run off of the main trunk duct served by the rooftop unit. The rooftop unit supplies air into the main trunk duct and the individual zone thermostats modulate their respective dampers to supply the proper amount of air to their zones. Zones that have high demands for conditioned air will open their dampers fully, while zones with little or no demand will modulate their dampers closed, or to a minimum ventilation position.

As the individual zone dampers modulate closed, a bypass damper, located near the rooftop unit which connects the supply duct directly to the return duct, modulates open to allow the excess airflow and duct pressure to be relieved to the return air side of the unit. This bypass arrangement maintains constant airflow through the rooftop unit and ensures a minimum amount of air (and thus heat load) is being applied to the rooftop cooling coil at all times. This is important to prevent refrigerant from flooding back to the compressors. When larger amounts of air are being bypassed it means most of the zones being served by the rooftop unit are satisfied and the remaining zones are becoming satisfied. The monitor thermostat turns the rooftop unit off when all zone thermostats are satisfied. Most often a continuous fan operation is chosen to allow continuous circulation of air throughout the building. This keeps the air moving and stabilizes temperatures and improves comfort, as most occupants tend to feel more comfortable with some amount of room air motion; ventilation air is also assured.

On this type of system, it is advantageous if the rooftop unit is equipped with multiple stages of capacity control so the unit can reduce its capacity as the load on the evaporator coil drops, indicating a reduced cooling demand at the zones. This is especially true when using larger tonnage rooftop units (> 15 tons) which are serving large zones where load diversity is more prevalent. Larger areas tend to have more load variables (occupancy, solar gain, transmission gains, etc.) which means a higher propensity for the unit to be operating with a smaller percentage of zones requiring cooling. The ability of the unit to balance itself to these conditions contributes to equipment reliability (by preventing refrigerant floodback) as well as comfort.
Variable Air Volume (VAV) Systems

Packaged rooftop units may be well suited to operate in variable air volume (VAV) systems, and indeed are often a very attractive choice due to the economics involved. First costs, installation costs and freeing-up of lease-able floor space within the building have led to significant growth in the rooftop VAV market.

The VAV rooftop unit serves many zones within a building by supplying a varying amount of supply air at a constant supply air temperature. The quantity of air is regulated by either changing the speed of the fan (usually with a variable frequency drive - VFD) or by changing the flow characteristics of the fan wheel itself (with inlet guide vanes).

The supply air is discharged into the main duct and branches from this main duct are run to individual zones. Each zone has its own thermostat, which in turn controls a VAV box (damper). This damper opens and closes to maintain the zone setpoint by varying the airflow amount to the zone. Some VAV boxes contain heat sources such as electric resistance strip heaters or hot water coils. This allows some zones to receive heat while other zones receive cooling from the central rooftop unit. Some VAV boxes contain a fan (fan powered mixing box) to supply heat. During the heating cycle the primary air damper closes to a minimum position and the fan and heating coil are energized to provide heat to the zone. This minimizes the amount of reheat that is required. Reheating the cooled supply air is an expensive and wasteful way to achieve simultaneous heating and cooling and is often prohibited by many building codes.

Some significant differences between a true VAV system and the VVT system described earlier are the unit’s controls and the fact that in a VAV system the quantity of supply air flowing across the rooftop unit’s cooling coil actually decreases at part load (air is not bypassed from the supply to the return duct). When zone dampers close, total airflow to and from the rooftop unit is decreased. Also, the VAV rooftop unit is not turned on and off by a thermostat; rather it starts and stops by a time clock. When in the on (occupied) mode, the rooftop unit’s refrigeration capacity is controlled to maintain a constant leaving air temperature.

The zone loads served by a VAV rooftop unit may vary considerably and the unit must be able to adjust its capacity to match the zone loads as they change throughout the day. At full load, VAV boxes will be wide open and the airflow to and from the unit will be at full capacity. At part load, dampers will be modulating and the airflow in the system will decrease. The VAV rooftop unit’s integrated controller will stage its refrigeration capacity to maintain the desired leaving air temperature.

The most common forms of capacity staging are compressor cycling and compressor cylinder unloading. As mentioned earlier, compressor cycling involves simply turning individual compressors on and off. Cylinder unloading is the act of closing internal passageways within the compressor to prevent the compression and hence reduce the mass flow of refrigerant. VAV rooftop units that utilize cylinder unloaders typically control these unloaders via electric solenoid valves controlled by the discharge air temperature algorithm inherent in the control system.

Rooftop VAV units usually operate from a time clock and do not cycle on and off during the day like constant volume units. This means VAV units must be capable of operating over a wide variety of loading conditions; from full load, to very low loads, to anything in between. To balance itself to these varying conditions, the VAV unit should be equipped with as many capacity stages as possible in order to match the building load profile as closely as possible. Sufficient capacity stages will help prevent excessive compressor cycling and more accurately maintain the desired leaving air temperature.

Cycling compressors can be an effective method of capacity control if the unit has enough compressors to allow the unit to reduce its capacity as the building load drops. If not, excessive compressor cycling and poor temperature control may result. For instance, on a 30-ton packaged rooftop unit with two equally sized compressors, you have only two stages of capacity, each stage equal to 15-tons. If the building load is 20-tons, the second stage compressor must cycle on and off to attempt to match the building load. Likewise, if the building load drops to 10-tons the first stage compressor must cycle. This intermittent
cycling may cause accelerated wear and tear on the compressor and may cause swings in indoor temperature and humidity. The gap in unit capacity versus building load is shown in Figure 4.

![Unit Capacity vs. Building Load](image)

**Figure 4**

Cylinder unloading is a popular method of increasing capacity staging while minimizing compressor cycling and aids the unit control system by controlling the discharge air temperature setpoint. Keeping the discharge air temperature constant will also improve the humidity control within the building. With compressor cylinder unloading, the same 30-ton rooftop unit application, discussed previously, may now have multiple compressors with cylinder unloading to achieve as many as 6-steps of capacity. These additional capacity stages allow the rooftop unit to much more closely control its capacity to the actual building load. This means there is much less cycling of compressors which improves the unit’s performance and tends to provide a more stable control of indoor relative humidity and temperatures. A rooftop unit with six steps of capacity is shown in Figure 5.
When selecting VAV rooftop units, the minimum building load should be compared to the minimum possible capacity stage of the packaged rooftop unit. Ideally, the unit’s minimum capacity stage will be lower than the minimum building load. This will prevent evaporator coil icing, low suction pressure nuisance trips, or refrigerant floodback problems. Minimum load on the equipment can be found using load estimating and energy simulation software and minimum unit capacity can be obtained from manufacturers’ catalogs.

If the building load, at low load conditions, is lower than the minimum capacity stage of the equipment, then hot gas bypass may need to be used. Hot gas bypass is a common method of keeping the unit on-line when cooling requirements are critical. This method employs routing hot refrigerant gas from the refrigerant compressors directly to the evaporator coil to elevate suction temperatures and reduce the unit’s capacity. Hot gas bypass capacity control is energy inefficient and should be used only as a last resort. If low load conditions necessitate substantial amounts of time running in hot gas bypass modes, it would be advisable to look at multiple VAV rooftop units as one alternate solution.

An alternate energy efficient method of low load control available on some rooftop units is to have the discharge air controller actually cycle the last stage of compression based upon discharge air temperature. This method allows accurate discharge air control down to essentially no load without the use of hot gas bypass. Note this method of control is based upon supply air temperature and is not a coil or suction frost sensing routine - it is a control scheme not merely a safety mechanism.

**Conclusion**

Although packaged rooftop units must be selected for maximum design load conditions, they rarely operate at these design conditions. Care should be taken when selecting and laying out these units to ensure reliable operation along with proper temperature and humidity control. Building part load profiles should be analyzed and compared with the part load performance of the proposed equipment in order to ensure a successful union.
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