Why Packaged Equipment is Wrong for School Classrooms

Introduction and Background

Excessive humidity leads to sickness.

Too, too many classrooms, especially in the American South are conditioned with a small, single-package or split-system air conditioner. This is usually the least expensive option and for that reason, they often the top choice when budgets are considered. It's complicated, but the compromise that one must accept with such a system is that the classroom relative humidity will be excessive. This leads to mildew, mold, and sickness - sometimes subtly (i.e. allergies) but at other times more severe. In recent years, many school systems have been forced to close for days or weeks at a time because of the flu. Now with a COVID-19 pandemic raging, the problem is amplified.

This paper will show, from an engineering perspective, why the use of small packaged equipment is inappropriate and is contributing to the extreme magnitude of sickness in our schools today.

Prototype Load Calculation

School classrooms are similar in design.

A "typical" school classroom is one application that is actually close to typical for schools across the country. Sure, there is variety, but a 32'x24', 768 square-foot classroom having 24 students and one teacher would be easy to find in almost any city or town.

Our prototype classroom has a single North wall exposure. While many worry most about the classroom on the Southwest corner, it is the rooms having the least solar exposure that are at the highest risk for sickness. Our design conditions in Knoxville, Tennessee are 93 °FDB and 74 °FWB.

Thanks to today's energy codes, there is little to debate regarding the building envelope. A compliant classroom will achieve a consistent performance level with code-prescribed wall/roof/glass u-values and window shading coefficients.

Much attention is paid to the improvements made to building envelope performance; however, it is also important to understand that the envelopes have less infiltration today. Building codes are now very specific about in-leakage through a compliant building, so infiltration becomes easy to estimate and document. Our buildings are much tighter now!

Lighting is also easy to quantify by code and since LED lighting has enjoyed wide acceptance by most, actual lighting loads are coming in below code mandated values. Even with a nominal number of computers or tablets, interior equipment loads are generally a small percentage of a school classroom cooling load.

So far, we have discussed cooling load components that are almost entirely sensible loads. Infiltration does have some latent load on warm humid days. These loads have been reduced in recent years by energy conservation efforts, but also welcomed by Owners anxious to save utility costs. Progress!

Ventilation loads have increased in terms of percentage.

Less understood by many engineers is the reality that people and ventilation loads, which have not been reduced, have now increased as a percentage of the overall load. This lowers the space and unit sensible heat ratios (SHR). One result of the change is that an acceptable unit to serve the classroom must now have a lower apparatus dewpoint temperature (T_{ADP}) to function well. Here, "function well" means maintaining a relative humidity in the space that avoids a risk of sickness for its occupants.

A classroom having 24 students and a teacher will require 250 cubic feet per minute (cfm) of fresh air plus 0.12 cfm per square foot (sf) of floor area (per mechanical code). This equates to 342 cfm. From there, one must divide by 0.8 if the return is not at the floor. Most classrooms that are budget limited to small packaged units will not include a floor mounted return, so we accept the penalty here. So, 428 cfm of fresh air ventilation is required for our prototypical classroom.

The small details of our prototype load calculation would unnecessarily complicate this paper, but we have summarized the results below (Figures 1 and 2). A simple look at the pie chart shows that 76% of the classroom cooling load are components that have very high latent loads. This is a real challenge for a packaged HVAC system!

A typical classroom has load characteristics like these...

	Sensible Heat (Btuh)	Latent Heat (Btuh)	Totals (Btuh)	Percentage of Total
Space Load Values				
Walls	191	0	191	1%
Windows	1661	0	1661	5%
Roof	985	0	985	3%
Infiltration	428	339	767	2%
People	6125	5125	11250	32%
Lights	2675	0	2675	8%
Equipment	2132	0	2132	6%
Supply Fan	694	0	694	2%
Space Subtotals	14891	5464	20355	58%
Coil Load Values				
Ventilation	8247	6587	14834	42%
Coil Subtotals	8247	6587	14834	42%
Total Load Values	23138	12051	35189	100%

Figure 1 - Prototype Classroom Load Summary

From this summary, we can determine the space sensible heat ratio (SSHR) as the space sensible heat (SSH) divided by the space total heat (STH) value.

$$SSHR = SSH / STH = 14{,}891 / 20{,}355 = 0.73$$

Ventilation, People, and Infiltration are 75% of the classroom load!

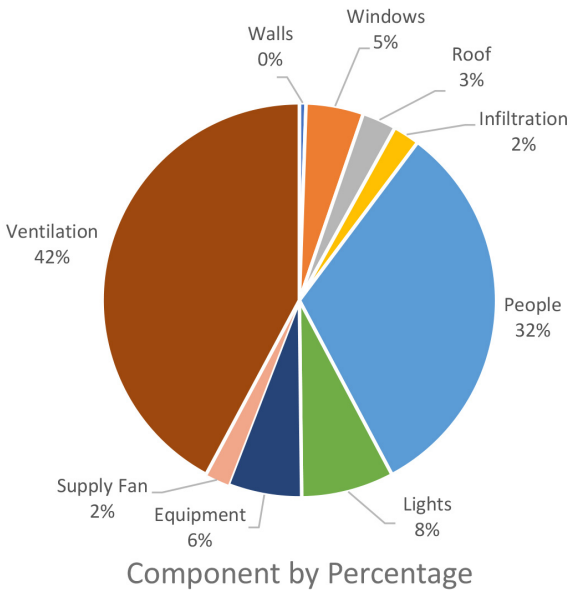

Figure 2 -Visual Chart of Classroom Load Components

Optimal Equipment Selection

For a given load requirement, an optimal unit coil selection exists.

It may come as a surprise to some, but optimal equipment selection begins with a psychrometric chart, not a manufacturer's catalog. For a given space and load calculation, there is an optimal coil for that application, or at least a small number of alternatives. We will explore the optimal coil condition for our prototype classroom here. A description of the calculation will follow, but a simultaneous reference to Figure 3, a psychrometric chart, is suggested.

First, we will plot a line from our design outdoor condition (Point 1) to the desired space condition (Point 2). By energy code (IECC 2018-C302.1), our entering condition will be 75 °F, which is admittedly a bit higher than most folks set their thermostat.

The way I choose to look at it, if our thermostat is set a bit lower but it can only maintain 75 on a hot design day, then who am I to complain? We choose to select 50% relative humidity, as we feel that it is the midpoint in that 40-60% range that most research recommends for public health. Also, many psychrometric charts have historically highlighted that point as a bulls-eye on their published charts. So, this outdoor-to-space line is shown accordingly (Point 2).

Second, we will plot a line from the space condition (Point 2) toward the saturation curve at a slope of the space sensible heat ratio (SSHR=0.73) . We will extend this line to the saturation curve (Point 4) and record the resultant dewpoint temperature of (T_{ADP}=47.8 °F). This is the approximate required apparatus dewpoint (surface temperature) of a coil which can produce the desired space condition. The precise value is actually a bit less. Forty seven degrees is quite cold! Only very specialized packaged equipment can meet the this requirement. Chilled water is usually required.

History is a great source for design fundamentals.

From this point, one must make an assumption of bypass factor for a coil. That goes beyond the scope of this paper, but a value of 0.10 is convenient, achievable, and appropriate. A bypass factor represents the amount of airflow through the coil that avoids the effect of the coil's surface. In other words, air that manages to bypass the coils influence. Historically, this concept was presented by Willis Carrier et al. in 1940 and later part of the industry-standard Carrier Design Manual (1960). While the importance of the bypass factor has not changed, its mention and discussion is rarely encountered in today's conversations.

Although an assumption of bypass factor is made here, it should be later confirmed by a valid coil selection (will a packaged unit work - probably not!). Some designers will simply place this point on the 90% saturation line. That will generally work, but it compromises technical correctness (and understanding of the coil bypass factor). To be absolutely correct, the bypass point should be placed on the actual coil line, not simply on the straight line plotted to dewpoint. But, this is for advanced study and does not impact the result significantly.

So, a leaving coil condition can be plotted on the space-to-saturation line. That part will be 10% of the temperature difference or

$$T_{LDB} = T_{ADP} + 0.10\,(T_{SPACE} - T_{ADP})$$

$$= 47.8 + 0.10\,(75.0 - 47.8)$$

$$T_{LDB} = 50.5\ °F \quad \text{(Point 6)}$$

Once the T_{LDB} point is located on the space-to-saturation line, the leaving wet-bulb temperature (T_{LWB}) can be read from the chart. In this case,

$$T_{LWB} = 49.4\ °F.$$

If one lacks an understanding of any of the above, the Carrier Design Manual, originally published in 1960 but still widely available, is an excellent tutorial on psychrometrics.

So, at this point we know that our leaving coil condition (Point 6) needs to be 50.5 °FDB and 49.4 °FWB in order to meet our desired space condition. Can packaged equipment do this - probably not!

Next, we need to establish the required airflow. Since we know our space sensible heat (Q_{SPACE}, from our load calc) and have now calculated the coil leaving air temperature, the determination is simple.

$$CFM_{SPACE} = Q_{SPACE} / 1.08 \times (T_{SPACE} - T_{LDB})$$

$$= 14{,}891 / 1.08 \times (75.0 - 50.5)$$

$$CFM_{SPACE} = 563$$

Now that we know our space airflow, we can calculate our entering coil condition based on outside air requirements and outdoor design conditions.

$$T_{EDB} = T_{SPACE} + [(CFM_{OA} / CFM_{SPACE} (T_{OA} - T_{SPACE}))]$$

$$= 75 + [(428/563 (93-75))] = 75 + 13.7$$

$$T_{EDB} = 88.7\ °F \text{ (Point 7)}$$

By plotting the T_{EDB} value on the outdoor-to-space line, the entering wet-bulb temperature T_{EWB} value can be read from the chart. In this case, $T_{EWB} = 72.3$ °F.

Finally, the required unit sensible and total heat values can be calculated. Note the introduction of h_{EAT} and h_{LAT}, these are enthalpy values read from the chart.

$$Q_S = CFM_{SPACE} \times 1.08 \times (T_{SPACE} - T_{LDB})$$

$$= 563 \times 1.08 \times (88.7 - 50.5)$$

$$Q_S = 23{,}227 \text{ Btuh}$$

$$Q_T = CFM_{SPACE} \times 4.45 \times (h_{EAT} - h_{LAT})$$

$$= 563 \times 4.45 \times (35.2 - 20.0)$$

$$Q_T = 38{,}081 \text{ Btuh}$$

Equation factors (1.08 and 4.45) are utilized as sea-level values so as to reconcile with graphical values from the sea-level psychrometric charts that are available. Software can resolve with more accuracy, but without the value of illustration.

Finally, our optimal classroom unit performance data can be summarized:

A summary of optimal unit/coil values...

Space SHR	0.73
Desired Space Condition (T_{SPACE})	75.0
Design Outdoor Condition (T_{OA})	93.0
Required Ventilation (CFM_{OA})	428
Unit Airflow (CFM_{FAN})	563
Entering Coil Condition (T_{EDB}/T_{EWB})	88.7/72.3
Leaving Coil Condition (T_{LDB}/T_{LWB})	50.5/49.4
Unit Sensible Heat (Q_S)	23,227
Unit Total Heat (Q_T)	38,081
Unit Sensible Heat Ration (SHR)	0.61

These calculations and point values are graphically summarized in Figure 3, below. In particular, note the line at Note 9, which illustrates humid conditions that will exist with most packaged equipment.

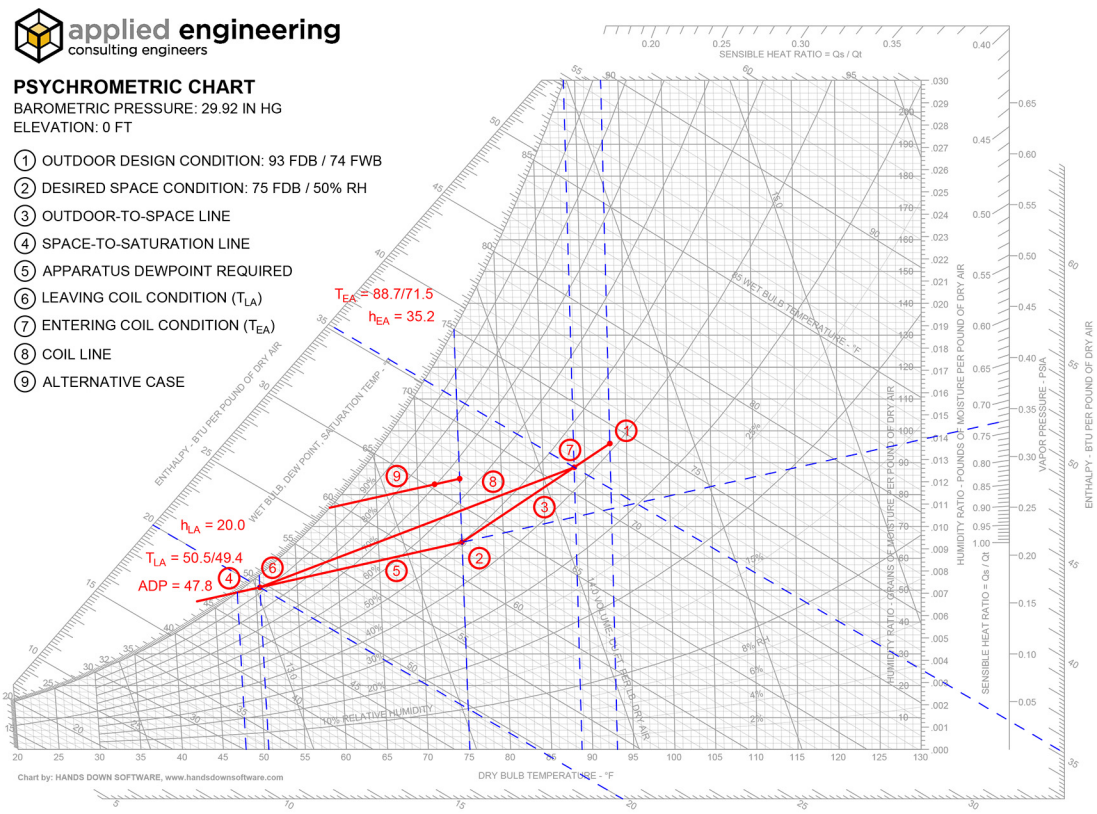

Figure 3 - Psychrometric Process for Optimal Coil

Whew, that was a chore! Nevertheless, at this point we now have a very informative summary of what it will take to condition our classroom properly. We'll call this an optimal selection for our prototype classroom.

The optimal values are nowhere near typical packaged equipment!

Now for some observations! The optimal classroom cooling coil has a total capacity of 35,189 Btuh, or just under three tons. The unit airflow is 563 cfm, or 188 cfm/ton. This value is only 47% of the typical packaged unit - they are normally rated at 400 cfm/ton. The outside air quantity is 428 cfm, or 76% of the unit airflow, far above any manufacturer's recommendation. The unit entering temperature is 88.7 °F, far above the unit rating point of 80 °F. In every metric, the typical small packaged unit is unsuitable for service in our prototypical classroom.

And, it is not as if things were that much different prior to the adoption of energy codes. While those changes were significant and took these metrics in the wrong direction, an analysis of a pre-energy code classroom results in a similar mismatch, just not as severe.

While DOA systems and ERVs can help, they don't exist on most schools.

It is true that a dedicated outside air (DOA) system can rectify this problem. An energy recovery ventilator (ERV) can make the problem less severe. Unfortunately, a small minority of classrooms have these systems. Further, owners and performance contractors have been known to not operate those systems, in favor of the utility savings that result.

Essentially, if a small packaged unit is the only conditioning device in a classroom, there is likely a problem with humidity and indoor air quality.

Using a Sub-Optimal Unit

We have shown the challenge of using a small, packaged unit for classroom applications. In almost all cases, these units are not up to the task. So what occurs if such a unit is in fact utilized?

First, the air temperature leaving the unit will be much higher than optimal, usually in the high 50′s, rather than the (very) low 50′s. With this as a given, one would then move the space-to-saturation line up on the chart such that the leaving air temperature will meet the temperature that the unit can provide. The slope of that line will remain the same (0.73), so one can then plot a resultant space condition where the line intersects with the space dry bulb temperature.

This condition is partially illustrated at Note 9 on the psychrometric chart. If a unit has a discharge setpoint of slightly less than 60 °F, then the resultant relative humidity will be about 65% at the code-driven setpoint thermostat setpoint of 75 °F. However, if the setpoint is at 72 °F (more common), then the space relative humidity rises to over 70%!

It is interesting to note that in 2019, ASHRAE downgraded its indoor air quality standard (Standard 62.1) to accept space conditions up to 60 °F dewpoint. Endorsing these conditions is inexcusable from a public health perspective, as relative humidity levels that result from 60 °F dewpoint exceed the recommendations of medical experts.

Closing ventilation dampers is the action that leaves a classroom as a super spreader!

Sadly, the usual response to the use of a small packaged unit in a classroom environment is to close the outside air damper, thus eliminating any dilution ventilation that the occupants would otherwise receive. This eliminates the humid outside air burden, and the classroom is now (seemingly) more reasonably conditioned. However, the lack of dilution ventilation will now allow any viral loads within the classroom to grow. CO2 levels rise, leaving students sleepy and less attentive. Others are subjected to them, and the probability of transmission rises. This condition only has to exist in one classroom common to many students to spread illness; when it occurs in most of them, further spread occurs.

Conclusion

There has been no shortage of studies regarding the impact of the classroom environment on learning. Study after study tells us that indoor air quality is important to the development of cognitive skills in an educational setting. Heck, comfort alone should be the criteria, and 70% relative humidity is certainly not a comfortable level. Rather, it is a level at which bacteria, viruses, mold, allergies, and other threats to health thrive.

Even worse than the threat of high humidity levels is the practice of closing ventilation dampers, manually or through software. Disabling ventilation, especially with tight building construction subjects students to increased viral loads, increased CO2 levels, and just plain old stale air. The sickness that is spread through the classroom eventually returns to the community as a whole, affecting parents, friends, and others that they interact with.

Although close to 90% of Tennessee's high school students graduate, less than 30% are considered to be proficient in math. As we endure the Covid pandemic, that number has fallen somewhat closer to 25%, only one in four students! Math is considered to be the prime subject for developing skills in logic and reasoning, skills that are so desperately needed in today's society.

In the not-so-distant past, a school closure of days to weeks for sickness was unheard of. Today, those closures occur with regularity. In December of 2014, the Tri-Cities area of Tennessee was reported to be the "sickest city" in America by USA Today. In 2015, Walgreen's Pharmacy reported Knoxville to be the number one area for flu activity in America. In 2020, WUOT Radio noted that school closures were common in Tennessee, but not so in other neighboring states. On October 2, 2021, the Knoxville News Sentinel headline was "Tennessee Leads in School Closures."

What are the factors at work here? Have the teachers changed? Has parenting changed? Have the students changed? Or, could it be something related to the classroom environment, especially HVAC?

We feel that the practice of using packaged equipment, which has itself changed in the last ten to twenty years, is a significant, if underlying factor that contributes to the extreme sickness that is being experienced and have shown that from an engineering perspective within this paper. Our students deserve better!

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