



HOW TO IMPROVE ASHRAE 55 AND MAKE IT MORE RELEVANT

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ABSTRACT

ASHRAE 55 is a standard that provides a way for occupant thermal comfort to be measured for building designs. It goes beyond air temperature to account for a range of factors, so that a more holistic assessment of occupant thermal satisfaction can be measured.

The standard needs to improve for two key reasons. Firstly, the comfort targets it sets are unachievable when Operative Temperature is measured by universally accepted methods. Secondly, an alternative method for measuring Operative Temperature allows almost all designs to comply and undermines a substantial part of the original intent of the standard.

This paper uses analysis to support these claims and proposes changes that would bring the standard back up to a level where it can be effective in its purpose.

INTRODUCTION

The use of ASHRAE 55 as a way to help designers implement better thermal comfort needs to be changed. When using a thermal analysis method based on the main body of the standard to test for compliance, it is virtually impossible to pass in most all US climate zone winter conditions. However, when using Appendix A as an alternative means of determining Operative Temperature, almost all air-conditioned buildings pass.

The main requirements of the standard are very hard to meet. With a typical heating setpoint of 21°C (70°F), ASHRAE 55 effectively requires a room on the perimeter to achieve a Mean Radiant Temperature (MRT) above 19°C (65.5°F) during all occupied hours. Internal surface temperatures of external walls, roofs and floors realistically likely to be much colder than this in North American winters.

Meanwhile ASHRAE 55 is used by the LEED rating system as the basis for its thermal comfort credit. The

GBCI (certifying body for LEED) reports that around 80% of projects submitting for LEED compliance, pass the thermal comfort credit. Almost none of the projects reported to pass use thermal analysis. Instead, ASHRAE 55's Normative Appendix A allows operative and air temperatures to be considered as equivalents if two very low bar prescriptive requirements are met.

This paper uses thermal analysis of a simple building form in Oakland, CA to demonstrate why it is hard to meet the standard requirements of ASHRAE 55. The analysis shows that in winter, even in Oakland with a highly insulated façade, Mean Radiant Temperatures in perimeter zones are too low to pass the standard.

This paper also compares Operative Temperature results approximated from Appendix A with simulated Operative Temperature results in summer and winter.

Note: Unless stated otherwise, it should be assumed this paper is referring to ASHRAE 55 (2013). Also note this paper only considers ASHRAE 55 through the lens of buildings fully-conditioned with non-radiant systems.

OVERVIEW OF REQUIREMENTS

This first section of the paper explains why ASHRAE 55 is so difficult to achieve using analysis. It covers:

- An interpretation of what the requirements for ASHRAE 55 (2013) are.
- A high-level explanation why these requirements are so hard to achieve.
- Method and results from the thermal simulation of a typical building to support the high-level assumptions.

Interpreting ASHRAE 55 (2013)

ASHRAE 55 (2013) runs almost 60 pages long and includes lots of detail and supporting guidance added to help practitioners. The standard is largely based on the concept of “Predicted Mean Vote” (PMV), a metric that

combines all comfort factors and combines them into a single value assessing the overall perception of comfort. The opening sections of the ASHRAE 55 (2013) standard outline these 6 factors that “shall be addressed when defining conditions for acceptable thermal comfort.

This section covers the determination of the following six factors in steady state. All six factors shall be addressed when defining conditions for acceptable thermal comfort:

- Metabolic rate
- Clothing insulation
- Air temperature
- Radiant temperature
- Air speed
- Humidity

Figure 1: Excerpt from section 5.1, ASHRAE 55 (2013)

If the mix of these conditions is right, a low number of occupants are predicted to be dissatisfied. The formula used calculates “Predicted Mean Vote” (PMV) which can also be expressed as “Predicted Percentage Dissatisfied” (PPD).

To simplify the notion of PMV, ASHRAE 55 has often sought to standardise the non-temperature inputs and then combine Air Temperature and Radiant Temperature into a single measure called Operative Temperature.

Measuring Comfort in the Standard

There are essentially two pathways a practitioner can follow to demonstrate compliance with the standard for normal air-conditioned buildings:

- A “Graphic Comfort Zone Method” allowable for more conventional buildings which lets the user plot their Operative Temperature condition on a modified psychrometric chart
- An “Analytical Comfort Zone Method” which looks for a PMV within ± 0.5 .

Both calculations are intended to represent pretty similar outcomes – a predicted satisfaction rate of 90% for building occupants. In other words, at the heart of ASHRAE 55 is an expectation that 90% of occupants would vote that they are “satisfied” with their thermal environment at all times.

A very high expectation of performance

The target of achieving 90% predicted satisfaction is onerous in comfort terms and is virtually impossible to achieve using simulation with a conventional system. Figure 2 summarises the Operative Temperature requirements to achieve this level of thermal comfort.

Although this is a psychrometric chart, the x-axis shows operative temperature, not dry bulb temperature. The standard is not explicit on when temperatures need to

fall within the shaded zones, but the implication is that *all* occupied hours are expected to comply (at least on a design day).

This means, in simple terms, that an Operative Temperature of 20°C / 68°F must be achieved at all times.

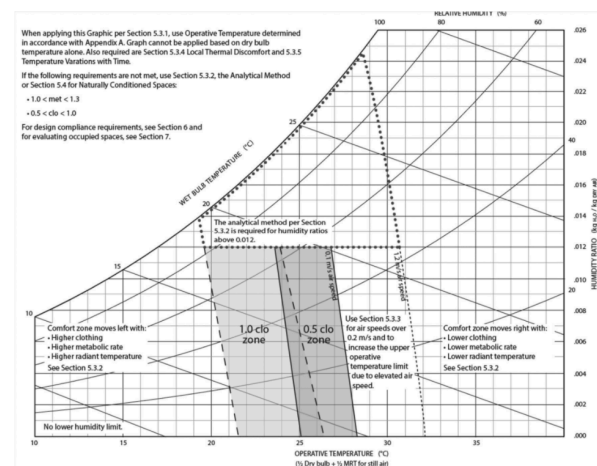


Figure 2: Chart showing the “Graphic Comfort Zone Method” in ASHRAE 55 (2013) p9

Why achieving 20°C / 68°F Operative Temperature during operating hours is very hard

Start with the following assumptions:

- Operative Temperature is the average of Radiant and Dry Bulb Air Temperatures – true in winter when airspeeds are low.
- During cold conditions, convective HVAC systems (like VAV) are in reheat mode, meaning the zone temperature is maintained at the bottom of the typical setpoint range of 21–24°C (70–75°F) to save energy.

A reasonable interpretation of the standard is therefore that Radiant Temperatures, in every zone, need to be at least 19°C (66.5°F) during all operating hours.

This can be quickly tested by considering a perimeter zone with a depth of 4.6m (15ft) and ceiling height of 2.7m (8.9ft). The MRT in this zone at any given timestep will be driven by internal temperatures of the internal and external walls, roof and floor.

In winter, during the first occupied hour, the table below summarises what might be expected for internal surface temperatures of these planes if the overnight low was 0°C / 32°F.

The process in Table 1 shows that by just making some quick theoretical assumptions about surface temperatures, it’s hard to imagine the MRT being consistently high enough to meet the ASHRAE 55

Operative Temperature target of 20°C (68°F) given typical operation of an efficient building.

Table 1: Rough MRT calculation

Surface	Internal Surface Temps	Reason for assumption
Internal Wall	19°C / 66.5°F	Tracked internal air temps overnight but warmup has not yet got it to 21°C
External Glazing	13°C / 55°F	Midpoint of glazing between 0 and 21°C. Internal surface is a bit warmer.
External Wall / Roof	15°C / 60°F	Lower midpoint that glazing due to mass but more insulation.
Ground Floor	14°C / 58°F	Influenced by ground temperature but slowly approaching space temperature
MRT	16.5°F / 63°F	Somewhere in the middle of the above surfaces, depending on zone geometry.

Simulation of Operative Temperatures - Method

This was studied further through a thermal analysis study of a basic office building, sited in Oakland, CA.

A simple, three story building, 20m x 60m with 4.6m perimeter core zoning and a glazing ratio of 40% (what is required by the ASHRAE 90.1 Baseline model) was used for the analysis. The model was built in SketchUp (see below) and simulated in EnergyPlus using Sefaira.

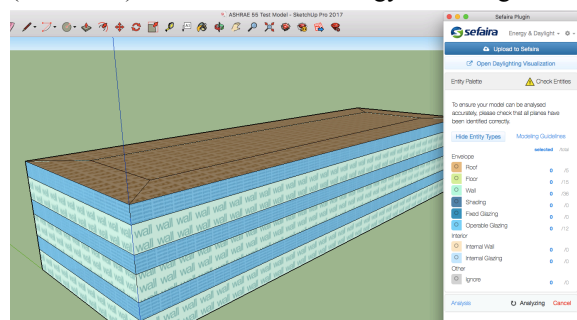


Figure 3: 3D model of simple building geometry

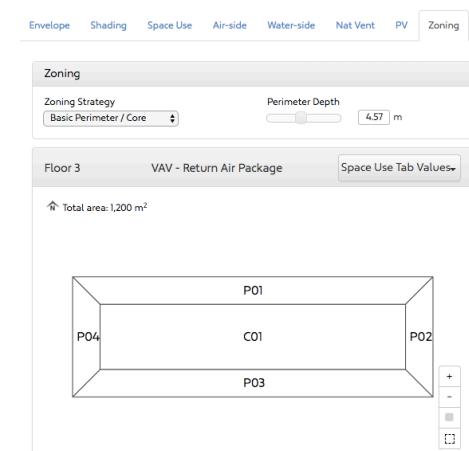


Figure 4: Perimeter Core Zoning layout used in Sefaira

Three options were simulated. The envelope inputs for these options are described below and were the only input values that varied by option:

Option	Envelope Properties
ASHRAE 90.1 Baseline	ASHRAE 90.1 (2010) for climate zone 3C (Oakland).
Best Practice Insulation	Per baseline with the following edits: Glazing Assembly U-value: 1.8 W/m ² /°C (0.32 BTU/h/ft ² /°F) Wall Assembly U-value: 0.2 W/m ² (30 ft ² .h.°F/BTU) Roof Assembly U-value: 0.1 W/m ² (50 ft ² .h.°F/BTU) Floor Assembly U-value: 0.2 W/m ² (30 ft ² .h.°F/BTU)
Best Practice plus shading (summer only)	Per Best Practice Insulation with the following edits: Shading: 1:1 horizontal shading on all orientations.

Other inputs were as follows:

- Location and weather file was based on Oakland, CA
- HVAC system was VAV Rooftop Package Unit with HW reheat configured per the ASHRAE 90.1 App G System 5 baseline with a supply air temperature of 13C / 55F.
- Warm-up was assumed to be 1 hour.
- All zones were assumed to be office space with internal conditions typical of offices and hours of operation 8am to 6pm, Monday to Friday.

Where possible, requirements for modeling a baseline option in ASHRAE 90.1 (2010) were used.

Simulation Results - Winter

Sefaira provided the EnergyPlus Operative Temperature results to an hourly spreadsheet of values. The results are for the North Perimeter zone (the worst-performing zone) as it's assumed all occupied zones must pass in ASHRAE 55.

Operative Temperatures (generated by EnergyPlus) for the ASHRAE 90.1 baseline materials and best practice insulation are plotted in Figure 5. The green shaded box shows operating hours and the standard's minimum required Operative Temperature of 20°C (68°F). The orange shaded box helps illustrate where each option fails to achieve the ASHRAE 55 target during operating hours.

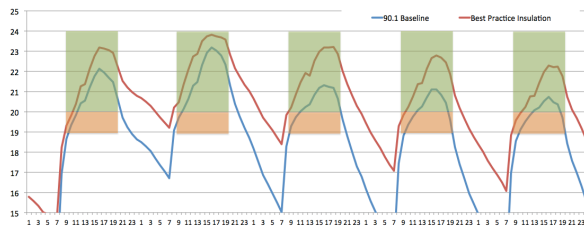


Figure 5: Hourly Operative Temperatures for north perimeter zone - typical winter week

For this week, there were 50 “occupied” hours. For both options, ASHRAE 55 Operative Temperature targets were missed for a substantial portion of hours:

- ASHRAE 90.1 (2010) default materials failed ASHRAE 55 Operative Temperature targets in 26% of operating hours.
- Best Practice Insulation failed ASHRAE 55 Operating Temperature targets for 10% of operating hours.

The failure rate over the year is shown in Figure 6.

Key observations:

- This ASHRAE 90.1 baseline model in a mild climate, fails ASHRAE 55 in a winter condition for 11.8% of all operating hours.
- With good practice insulation added while retaining 40% glazing, it still is not possible to pass ASHRAE 55 in winter for Oakland.
- Many new buildings nationwide have more than 40% glazing. It should be expected more glazing would increase the failure rate.

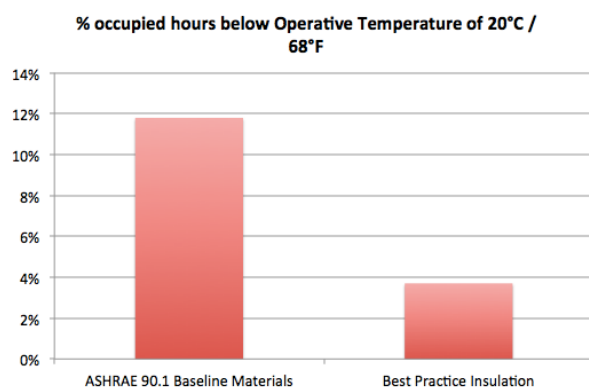


Figure 6: ASHRAE 55 failure rate for calculated Operative Temperatures below 20°C / 68°F

- Most North American cities are much colder than Oakland, and this should be expected to increase the failure rate.
- Increasing the winter setpoint to 24°C / 75°F was simulated and results in a winter pass,

however this is not how the building would be designed to be controlled in practice.

Further research is strongly recommended as on this basis almost no buildings in North America should be expected to comply with ASHRAE 55. This is because the minimum Operative Temperature target is too high.

Simulation Results - Summer

We used Sefaira to output the EnergyPlus PMV results to an hourly spreadsheet of values, then chose to review results for the warmest week of the year (August 7-11) in the Oakland, CA weather file. The results are for the West Perimeter zone (the worst-performing zone) as it's assumed all occupied zones must pass in ASHRAE 55.

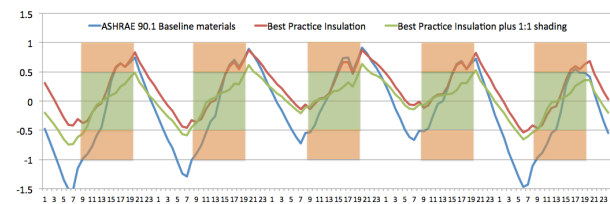


Figure 7: Hourly PMV values for west perimeter zone - typical summer week

The Y-axis shows PMV as calculated by EnergyPlus, using Clo values based on the morning temperature, Met values of 1 and Air speed of 0.2m/s.

To pass ASHRAE 55, the PMV should be between -0.5 and +0.5 so the chart shows that range coloured in green for operating hours. Failing zones are shaded in orange for operating hours. Key findings:

- To pass ASHRAE 55 (2013) with this shading model using a PMV calculation for summer conditions, it is necessary to have external solar control equivalent to 1:1 shading.
- These results show a west-perimeter zone with 40% glazing and ASHRAE 90.1 (2010) baseline materials for climate zone 3A failing the PMV target both in the morning and in the afternoon on most days.

Anecdotally there would seem to be many projects that pass LEED (and therefore lots that achieve the LEED Thermal Comfort credit) with more than 40% glazing on the west façade and without any solar shading.

Analysis conclusions

Based on both the summer and winter results, it can be concluded that ASHRAE 55 is very stringent in its requirements. Projects obtaining credit for Thermal Comfort in LEED would be expected to have very low glazing ratios, solar shading and sophisticated setpoint controls. These features are arguably not common in modern building stock.

NORMATIVE APPENDIX A

ASHRAE 55 in LEED, WELL, GreenStar

ASHRAE 55 is enshrined in many standards and has been for over a decade. These standards include LEED (all the way back to version 2), WELL and GreenStar (used in Australia). Many projects have been awarded points for “achieving thermal comfort” by demonstrating compliance with ASHRAE 55.

The thermal comfort credit in LEED is one of the most frequently complied with credits. The GBCI estimated that around 80% of projects submitting for LEED, pass the LEED thermal comfort credit. Meanwhile, very few projects were reported to use thermal analysis to comply with ASHRAE 55.

The main reason for this would seem to be Normative Appendix A (ASHRAE 55, 2013), which provides a way for almost any air-conditioned building to pass ASHRAE 55.

Normative Appendix A explained

As stated, the opening sections of the ASHRAE 55 (2013) standard outlines the 6 factors that “shall be addressed when defining conditions for acceptable thermal comfort.” This requirement is at odds with the method used to “Determine Operative Temperatures in accordance with Normative Appendix A”

This section covers the determination of the following six factors in steady state. All six factors shall be addressed when defining conditions for acceptable thermal comfort:

- a. Metabolic rate
- b. Clothing insulation
- c. Air temperature
- d. Radiant temperature
- e. Air speed
- f. Humidity

Figure 8: Excerpt from section 5.1, ASHRAE 55 (2013)

Normative Appendix A has been included at the end of ASHRAE 55 for a very long time. The requirements have remained the same, although the actual Appendix that it is included in has varied based on the standard.

Normative Appendix A provides guidance on how to calculate the Operative Temperature. There are 3 ways (or options) Operative Temperature may be calculated:

- A. Per chapter 9 of the ASHRAE Fundamentals
- B. Per 2 methods described in Appendix A
 1. Demonstrate its equivalence to Air Temperature
 2. Use a formula similar but not exactly the same as chapter 9 of the ASHRAE fundamentals.

Although option A and B.2 are slightly different calculations, for most air-conditioned spaces without exceptional air velocities, Operative Temperature approximately ends up being the average of mean Radiant Temperature and Dry Bulb Air Temperature.

It is case B.1 above that is exceptional. This is the text from ASHRAE 55 (2013), Appendix A:

Case 1: Average air temperature (t_a) is permitted to be used in place of operative temperature (t_o) when these three conditions are met:

- a. There is no radiant and/or radiant panel heating or radiant panel cooling system.
- b. The area weighted average U-factor of the outside window/wall satisfies the following inequality:

$$U_w < \frac{50}{t_{d,i} - t_{d,e}} \quad (\text{SI})$$

$$U_w < \frac{15.8}{t_{d,i} - t_{d,e}} \quad (\text{IP})$$

where

U_w = average U-factor of window/wall, $\text{W/m}^2\cdot\text{K}$ ($\text{Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F}$)

$t_{d,i}$ = internal design temperature, $^\circ\text{C}$ ($^\circ\text{F}$)

$t_{d,e}$ = external design temperature, $^\circ\text{C}$ ($^\circ\text{F}$)

- c. Window solar heat gain coefficients (SHGC) are less than 0.48.

Figure 9: Case 1 from Normative Appendix A, ASHRAE 55 (2013)

This text is essentially applying a prescriptive compliance pathway for the ASHRAE 55 standard. If the project achieves a basic U-value and SHGC, radiant effects may be ignored.

The standard arguably needs a prescriptive pathway to be applicable. Many of the software programs in North America used for energy analysis are based on DOE2 engines and do not provide Operative Temperature calculations. This means calculation of Radiant (and hence Operative Temperatures) has been outside the standard toolkit of most practitioners, necessitating a different way for radiant effects to be captured.

It is not clear where the prescriptive requirements enshrined in Appendix A come from. It is also not clear why they have not changed at all through the various other revisions of the ASHRAE 55 standard.

Given ASHRAE 55 is seemingly hard to comply with using analysis (refer previous section) it is reasonable to question the suitability of the prescriptive requirements in Appendix A. The next analysis focus of this paper was to try and see if a model that met the minimum

requirements in Appendix A could come close to passing the standard using the analysis methods outlined in the rest of the standard.

Analysis test of Appendix A - Method

To identify whether the prescriptive requirements would satisfy the performance based requirements of ASHRAE 55, a comfort simulation was run on a model complying with Appendix A inputs. The goal was to compare properly calculated Operative Temperatures against the approximations allowed in Appendix A.

The test was run for Oakland, CA.

For U-value:

- Design winter condition was 3°C
- Metric U_w required by Appendix A
 $= 50/(21^\circ\text{C}-3^\circ\text{C}) = 50/18$
 $= 2.78\text{W/m}^2/^\circ\text{K}$
- Option 1 – U-value for ASHRAE 90.1 baseline compliant façade was 3.69 for glazing and 0.48 for the wall (60%)
 $= 1.76\text{W/m}^2/^\circ\text{K}$ (well below App A)
- Option 2 - U-value for best practice option was 1.82 for glazing (40%) and 0.19 for the wall (60%)
 $= 0.84\text{W/m}^2/^\circ\text{K}$ (substantially below App A)

For SHGC

- SHGC in the model was 0.25, substantially below the required 0.48 in Appendix A.

Winter Results

The results below plot for the north perimeter zone in the middle floor of the box project in Oakland on the equivalent of a winter design day.

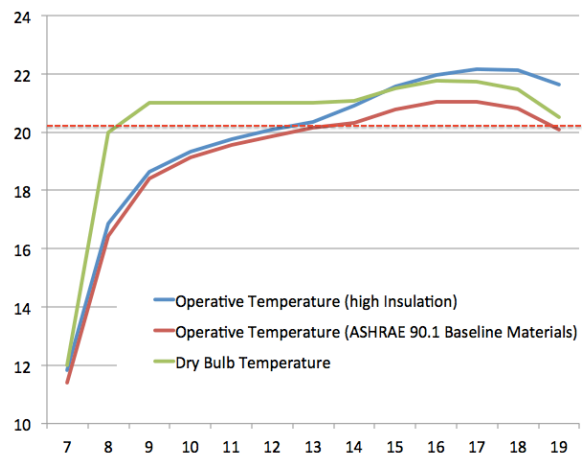


Figure 10: Calculated Operative Temperatures with Appendix A and improved façade inputs vs dry bulb temperatures

The red dotted line in the results shows the Operative Temperature needed to achieve a PMV at least -0.5 in winter (passing the standard). Actual Operative Temperatures, even with buildings that have much better insulation than required by Appendix A, are not able to achieve comfort until 1pm on a typical winter Monday. The Appendix A approximation, shown in green, does pass the standard but is found to be out by almost 3°C / 5°F as an Operative Temperature approximation.

Hot Day Results

The results are below plot for the west perimeter zone in the middle floor of the box project in Oakland on the equivalent of a summer design day.

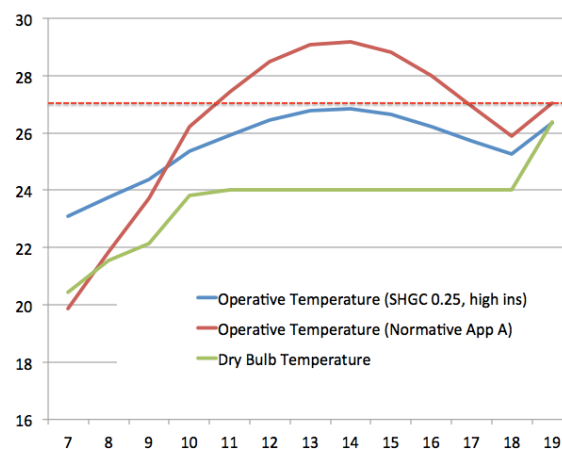


Figure 11: Calculated Summer Operative Temperatures for Appendix A and improved façade inputs vs Dry Bulb Temperature

The red dotted line conservatively shows how achieving a PMV <0.5 might be represented in terms of Operative Temperature - assumed to require an Operative Temperature below 27°C (80°F).

The first option (shown in red) is an ASHRAE 90.1 (2010) baseline façade for Oakland with the SHGC adjusted up to the allowed 0.48 value in Appendix A.

A second option (in blue) shows a higher performing variation on the baseline model, with better insulation and an SHGC of 0.25.

Both models still had 40% glazing and a 4.6m perimeter zone depth as in the original study.

The difference between what the Normative Appendix A allows as an approximation of Operative Temperature and the actual Operative Temperature is large – up to 5°C / 9°F. Based on this simple simulation, there is little evidence that Appendix A's approximation method for Operative Temperature is fair.

This is only a small study, and further analysis should be done to consider the applicability of Normative

Appendix A. Based on these initial studies it seems unlikely that it would be possible to validate the Appendix A approximation methodology in very many cases.

If this approximation methodology is confirmed to be this inaccurate, ASHRAE should strongly consider removing this Appendix and replacing it with prescriptive requirements by climate zone that would represent reasonable equivalence with the standard.

Other compliance issues – Zoning depth

There is other missing detail in the standard that arguably provides scope for arbitrary decision-making on the part of an analyst using ASHRAE 55 properly. One of these pertains to zoning.

The way a model is zoned will have an impact on the thermal comfort results. Specifically, the zone depth and ultimately location of the zone sensor in simulation is very important. This is because in most thermal models, the simulation point for a zone is the center of the zone.

The distance of the simulation point in any zone from hot or cold surfaces will change thermal comfort results because thermal comfort is influenced heavily by MRT. In order to understand how important this variable is, a simulation of the previous model was carried out, considering two different zoning strategies:

- The same perimeter/core strategy used for previous studies (depth 4.7m / 15ft)
- A one-zone-per-floor strategy.

Figure 12 plots operative temperature for these two zoning strategies on a winter day, with the south-facing perimeter zone compared with the whole floor zone.

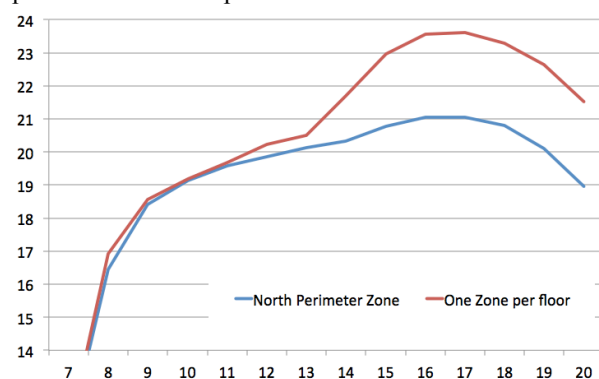


Figure 12: Operative Temperatures (°C) measured for South Perimeter Zone and Single Zone per floor with identical model and inputs – winter day

ASHRAE 55 does not really make it clear how someone doing simulation should zone their thermal model. It doesn't say to use the same zoning as the

energy model. It doesn't say to use the same zoning as in real life. This simple study puts forward a case for providing more clarity in the standard on how simulation models should address zoning when using a simulation method in the standard.

There is a standard perimeter/core definition for zoning in ASHRAE 90.1. This could form a good basis or starting point for a zoning requirement in ASHRAE 55, particularly given many practitioners doing performance-based calculations will use the same thermal model for both calculations.

RECOMMENDED CHANGES

Based on the two key issues with the standard identified in this paper, there is a need for further research and ultimately substantial changes to be considered to this standard. Based on the findings in this paper, the following changes are recommended:

Make it clearer what it is for

One probable cause of the current confusion in the standard is there does not seem to be clear direction on what the standard is actually for. For example, the following are reasonable questions that arise after reading the standard:

- Is the purpose of the standard to account for façade design variations?
- Is the purpose of the standard to improve HVAC design? If so, which aspects?
- Is the purpose of the standard to improve the design of naturally ventilated buildings?
- Is the purpose of the standard to predict actual comfort conditions?

All of the above are purposes that the industry probably perceives the standard as having.

The first recommendation would be for the standard to declare more clearly its purpose, especially as it applies to professional design. Some ideas that would make the standard more applicable as a methodology referenced by rating schemes would include:

- Helping design teams deliver façade solutions that reduce the discomfort from radiant temperature effects in air-conditioned buildings.
- Helping designers assess the suitability of natural ventilation designs and passive design strategies.
- Help designers understand the comfort differences between different HVAC design options and configurations, by factoring in the

expected air speed, radiant temperature and humidity control effects of those systems.

Make it achievable

PMV is arguably a well established and validated way to benchmark the mixture of factors that affect comfort. One argument might be that although PMV is a good benchmarking methodology, the ASHRAE 55 implementation of this is too stringent.

Before PMV targets are changed, it is recommended that research should be done to consider what best practice in different regions of the US (and ultimately the world) is, and normalise what kind of comfort performance those strategies are able to deliver.

PMV values could then be set based on that research, such that it would provide a performance-based pathway for compliance that also included clear prescriptive steps as to how it could be achieved.

Replace Normative Appendix A with well-researched prescriptive requirements

Based on analysis in this paper, Normative Appendix A does not reflect the intent of the standard in allowing an estimation of key variables and is therefore a poor way of providing a prescriptive compliance pathway for practitioners who are not able or willing to do proper simulation of their design.

It is very important for the standard to recognise that this is how it's being used and offer a meaningful prescriptive compliance workflow. Today, and for the foreseeable future, it might be unrealistic to expect most project teams to have access to simulations providing PMV or Operative Temperature results.

To do this, research needs to be carried out modeling a wide range of options for each climate zone. Prescriptive requirements might only apply to air-conditioned buildings and might focus on the following:

- Minimum design temperature and humidity ranges for HVAC operation
- Minimum assembly values for glazing, walls floors and roofs
- Minimum solar properties for glazing assemblies (that can account for shading)
- Maximum glazing ratios

The values would be expected to differ by climate zone.

Constrain variable inputs to things the designer is able to control, understand and measure

A clearer purpose makes it easier to know what practitioners are actually using the standard to design.

This should then help focus the standard on input variables that actually reflect what happens in real life.

For example, recent changes to the standard that look at determining average air temperature by considering temperature at 3 heights are both impractical to calculate and relevant only to a very small proportion of HVAC systems. If CFD-style analysis is to be required then it should only apply to systems that need that sort of analysis.

Similarly, key inputs like airflow rates should be linked back to design strategies known to the practitioner, like system type and/or supply air temperature. Where values can vary seasonally, software vendors should be consulted to make sure the dynamic variables can be analysed in a practical way.

SUMMARY

ASHRAE 55 has a huge amount to offer the industry. It still has a lot of goodwill and is based on a good formula for combining key comfort inputs.

There is work to be done, but with a bit of focus and purpose, along with some research support, it could be repurposed to be a relevant design tool that makes an important impact on future projects, as was its original intention.

ACKNOWLEDGMENTS

Big thanks mainly to Sefaira users who have provided feedback and guidance on this issue.

Thanks to GBCI, GBCA and others for candid feedback on the topic.

REFERENCES

The following documents and interactions informed this paper.

- ASHRAE Standard 55 (2013). Thermal Environmental Conditions for Human Occupancy.
- ASHRAE Standard 90.1 (2010). Energy Standard for Buildings Except Low-rise Residential Buildings. (including Appendix G)
- ISO 7730 (2005) Ergonomics of the thermal environment
- LEED NC 2009 Handbook, LEED v4 Handbook, WELL Building Standard
- ASHRAE Fundamentals Chapter 9
- Conversations with Green Building Certification Institute, Sept 2017
- Conversations with Green Building Council of Australia, Nov 2017
- Conversations with ASHRAE 55 Technical Committee members, Sept 2017