CAT on a Hot Tin Roof: Getting Climate Appropriate Technologies onto Rooftops in Hot Dry Climates

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ABSTRACT

Approximately 65% of the commercial building sector is cooled by roof top units (RTUs) that are designed and optimized for nation-wide application. California has a long-standing commitment to meeting aggressive carbon reduction objectives. Can RTU performance be optimized for California's unique climate? Would manufacturers be willing to produce solutions to meet these regional needs? To address these needs, the California investor-owned utilities and the Statewide Emerging Technologies program began a decade long effort to meet the challenge of getting climate appropriate RTUs onto California rooftops. This paper presents an accounting of the challenges along the way and the solutions that were employed to meet this goal, starting with the Western Cooling Challenge (WCC) to manufacturers, with efficiency targets based upon adding indirect evaporative cooling to direct expansion RTUs; >40% improvement in seasonal efficiency, and >50% improvement in peak efficiency relative to DOE 2010 minimum efficiency standard. The WCC incorporated lessons learned through research and demonstrations on RTU retrofits and has evolved towards innovative, less-costly solutions that add indirect evaporative cooling to existing RTUs. This paper presents the technical design of the WCC, laboratory and field test results for WCC technologies, laboratory and field test results for evaporative pre-coolers for RTUs. The paper also presents the development of an ASHRAE standard for testing RTU evaporative pre-coolers, including addressing value-chain acceptance issues, and water consumption concerns. The authors conclude with a discussion of the future of HVAC efficiency in California.

Introduction

California recognizes that maintaining its commitment to meeting aggressive carbon reduction objectives means addressing energy consumption throughout the economy. One sector of California energy use that has been challenging is space conditioning of small and medium-sized commercial buildings. Approximately 65% of the commercial building sector is heated and cooled by roof top packaged units (RTUs), complete air conditioning systems in a single box (California Energy Commission, 2006). Manufacturers design and optimize their RTU products for nationwide application, so their designs may be less-than-optimal for any particular individual climate. Moreover, with respect to cooling, these systems, dependent on location and climatic conditions, have a relative low load factor (~20%), which means that they represent a much larger fraction of summer peak electricity loads relative to their annual electricity consumption (Brown and Koomey, 2002). This situation raises a number of questions, including: 1) Can RTU performance be cost-effectively optimized to reduce energy consumption and peak power demand for California's climate zones?, and 2) Would manufacturers be willing to produce such RTUs to meet the needs of California? Both questions need to be addressed in order for California to reach its goals in this sector.

In an attempt to address this situation, California investor-owned utilities consisting of Southern California Edison, Pacific Gas and Electric, San Diego Gas and Electric, and Southern California Gas and the Statewide Emerging Technologies program began a decade-long effort to meet the challenge of getting climate-appropriate RTUs onto California rooftops. This paper describes that effort, including the challenges along the way and the solutions that were pursued to meet this goal. The effort started with the Western Cooling Challenge (WCC), which was designed as an offer to manufacturers to produce RTUs with a roughly 40% improvement in seasonal cooling efficiency, and more than a 50% improvement in peak cooling efficiency relative to the DOE 2010 minimum efficiency standard (Woolley and Modera 2011). The prize for manufacturers who met this challenge was the likely development of utility incentive programs to promote the accelerated adoption of such technologies. To not require a complete redesign and retool of manufacturing processes, these efficiency targets were calculated based upon adding indirect evaporative cooling to existing high-efficiency, direct-expansion RTUs. This was to show that these efficiency targets were achievable but manufacturers could meet the targets in any manner.

Based upon limited success with getting manufacturers to embrace the WCC, along with the realization that many RTUs last for a long time. An analysis of the 2003 Commercial End-Use Survey data indicated a mean age of 10 years, with 25% of units being more than 15 years old (California Energy Commission, 2006)and the desire to effect change more rapidly, the WCC evolved into an initiative to get existing RTUs retrofitted to approach WCC targets. This effort converged on laboratory tests and field studies to evaluate the effectiveness of adding indirect evaporative pre-coolers for condenser inlet air (and ventilation-air in some cases), and ultimately into the development of a currently-proposed ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) standard for testing the performance of evaporative condenser-air pre-coolers.

This paper presents the history of the strategic collaboration that led to the WCC, the impetus for the choices behind the technical design of the WCC, laboratory and field test results for WCC technologies showing the progressive development of the body of knowledge on pre-cooling technology, laboratory and field test performance results for evaporative pre-coolers for

RTUs, and some of the rationale behind the development of an ASHRAE standard for testing RTU evaporative pre-coolers. The paper concludes with a discussion of lessons learned, and the future of HVAC efficiency in California.

Background

Cooling and ventilation account for more than 25% of the annual electricity consumption for commercial buildings in California (California Energy Commission, 2006). If natural gas use is also considered, heating, cooling and ventilation typically account for more than 35% of the annual primary energy footprint for a commercial building (U.S. EIA, 2016). Air Conditioning accounts for more than 30% of the greenhouse gas emissions associated with commercial buildings in California, amounting to statewide emission of more than 7.5 MMT CO2e (Air Resources Board, 2009). Moreover, air conditioning is the largest single contributor to peak electrical demand. Rooftop units are usually the largest single connected load in a commercial building, and can account for more than 50% of the on-peak demand from commercial facilities. California's electric grid is especially stressed during summer periods when generation requirements can be twice as high as other seasons. On the hottest summer days, air conditioning alone accounts for more than 30% of the peak demand on the statewide electric network (Air Resources Board, 2009; CPUC, 2011). This situation becomes more complicated during swing seasons, when lower cooling loads, combined with non-coincident solar generation and vehicle charging, combine to create more complicated electricity load shapes and pricing signals (e.g. the "duck" curve).

In 2004, as part of the Pacific Gas & Electric emergence from bankruptcy, the California Clean Energy Fund (CalCEF) was created. When CalCEF created a competition to create the first Energy Efficiency Center at a university, the University of California at Davis won, based in part on their proposal to create the Western Cooling Efficiency Center (WCEC). The mission of the WCEC was to "Partner with stakeholders to identify technologies, conduct research and demonstrations, disseminate information, and implement programs that reduce cooling-system electrical demand and energy consumption in the Western United States." To help support this mission, all of the California investor-owned utilities, as well as the Sacramento Municipal Utility District, joined as corporate affiliates of the cooling center, along with major HVAC manufacturers, smaller companies with cooling-related products, and some large customers of unitary cooling equipment.

Western Cooling Challenge

As mentioned earlier, roof-top packaged units (RTUs) are complete air conditioning systems in a single box, as opposed to the air conditioning systems found in large commercial buildings that are built up from components based upon customized designs by HVAC consulting engineers. RTUs, because they are mass produced for nationwide markets, are not optimized for particular applications, nor even for particular types of climates (e.g. hot-dry versus warm-humid).

Knowing that these are mass-produced products for nationwide markets, our conversations with stakeholders (e.g. manufacturers and retailers), combined with the authors' experience with mass-production, led us to decide that major manufacturers were unlikely to produce from-the-ground-up designs, even for the California market with a promise of incentive programs. This meant that we needed to design the targets for the WCC in such a way that a major manufacturer could meet the challenge without necessitating a major RTU re-design. This did not preclude a complete new concept/design, but rather made it possible to meet the challenge without going back to the drawing board. The details of the WCC have been published by Woolley and Modera (2011), however some of the thinking behind the challenge design is worth highlighting here, as it demonstrates some of the challenges associated with trying to achieve our goal of getting energy-efficient, climate-appropriate RTUs installed on California rooftops:

- **Test Conditions –** Most test conditions differed from those in the industry-standard test procedure (AHRI Standard 340/360), including using lower indoor wet-bulb temperatures (i.e. drier indoor air), and two different outdoor air conditions that bracket the AHRI Standard 340/360 outdoor air test condition. One condition was chosen to represent more-typical conditions for energy-use calculations in California, and the other to represent peak cooling conditions in California. In addition, the wet-bulb temperature (i.e. humidity) of the outdoor air was specified to be representative of California climates that have significant cooling loads (Woolley and Modera, 2011). WCC and AHRI conditions are compared in Figure 1. Finally, the WCC included outdoor air supply (i.e. for ventilation) during testing, requiring a minimum of 120 cfm/nominal-ton-cooling (16.1 L/s/nominal-kW-cooling), based upon Title-24 ventilation requirements for California combined with typical equipment sizing (i.e. capacity per unit floor area) (Woolley and Modera, 2011).
- **Cooling Capacity –** AHRI Standard 340/360 uses total cooling capacity (sensible (temperature reduction) plus latent (water removal)), however the WCC used only sensible capacity for capacity and efficiency (COP) calculations. We decided that this would be more representative of actual operational performance in California. In addition, the WCC had to manage the fact that RTUs could be designed to make use of different quantities of outdoor air. To manage this, the sensible capacity and COP calculations did not give any credit for cooling of any outdoor air above 120 cfm/nominal-ton cooling (16.1 L/s/nominal-kW-cooling). Finally, the WCC put constraints on the capacity at the cooler test condition (at least 80% of nominal capacity) to assure that manufacturers did not trade off capacity to achieve efficiency.
- **Other Considerations –** The WCC required that any manufacturer demonstrate the capability to manufacture at least 500 units per year, so as to eliminate one-off prototype entries, and required that the entry have a cooling capacity between 3 and 30 tons. In addition, as we expected entries to use water in addition to electricity, the WCC included limits on water use per ton of cooling provided. Finally, the test procedure specified the external flow resistance that the equipment would be tested against, such that units that moved more air would work against larger pressure differentials.

It took many conversations with a number of manufacturers about the benefits of the WCC, before they committed to participating in the WCC; the potential for increased sales with the help of a possible utility incentive was not a sufficient motivator.These conversations focused on the existence of a market for WCC products, the rationale behind the unconventional test points, the costs associated with meeting the WCC, who would do the testing, the role that utilities would play, and in general how the WCC might help their companies. We ultimately had two manufacturers follow through to delivery of units to be tested. As it turned out, one unit, provided by a major manufacturer, was very similar to the unit that we simulated to develop the test specifications, and the second unit, provided by a smaller, more-nimble company, was a from-the-ground-up design.

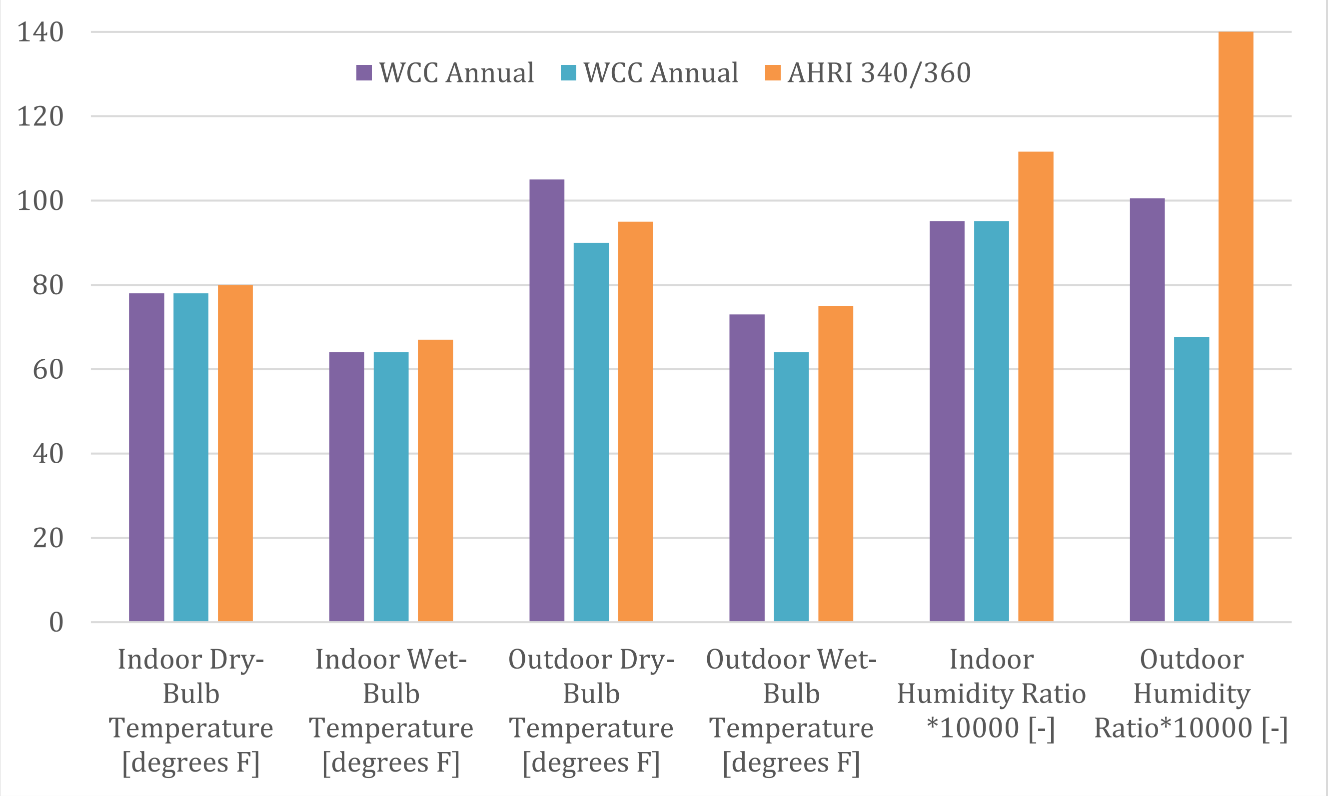

Figure 1: Comparison of Western Cooling Challenge test conditions with American Heating and Refrigeration Institute test conditions (AHRI Standard 340/360)

Laboratory and Field Studies

The WCC also included a promise to laboratory test entries provided by manufacturers, and so both entries were laboratory tested, albeit in very different ways with different challenges. The first entry came in before the test laboratory at the WCEC was built, and so we were grateful to National Renewable Energy Laboratory (NREL) to have them test that entry (Kozubal and Slayzak, 2010).. The results of that testing are included in Figure 2, which shows that its performance exceeded the challenge requirements by a considerable margin (50-75% higher COP), particularly for the annual test condition. . This was not surprising, as the first entry was a completely new design, while the WCC targets were set based upon relatively minor modifications to existing designs.

The second entry came in after the WCEC had been completed, however the new challenge was the capacity of the equipment to be tested was too large for the WCEC laboratory. In this case we contracted with a commercial equipment testing laboratory, which turned out to present its own challenges, the biggest one being that such labs are not designed for non-standard tests. The other challenges were to produce the highly dry conditions associated with the WCC, and that the laboratory was not designed to test equipment that introduces significant quantities of water into the condenser exhaust air. The key issue is that they are not generally equipped to remove significant amounts of moisture from the air entering the condenser, nor from the air exiting the condenser so as to make use of recirculation. An engineer from WCEC had to work very closely with the laboratory to resolve these issues and complete the test. The test results for this unit are also presented in Figure 2, which show that the second entry just about met the WCC specifications at peak conditions. The test facility was unable to conduct the test at the nominal annual test condition, so there is no data presented for the second entry at that condition.

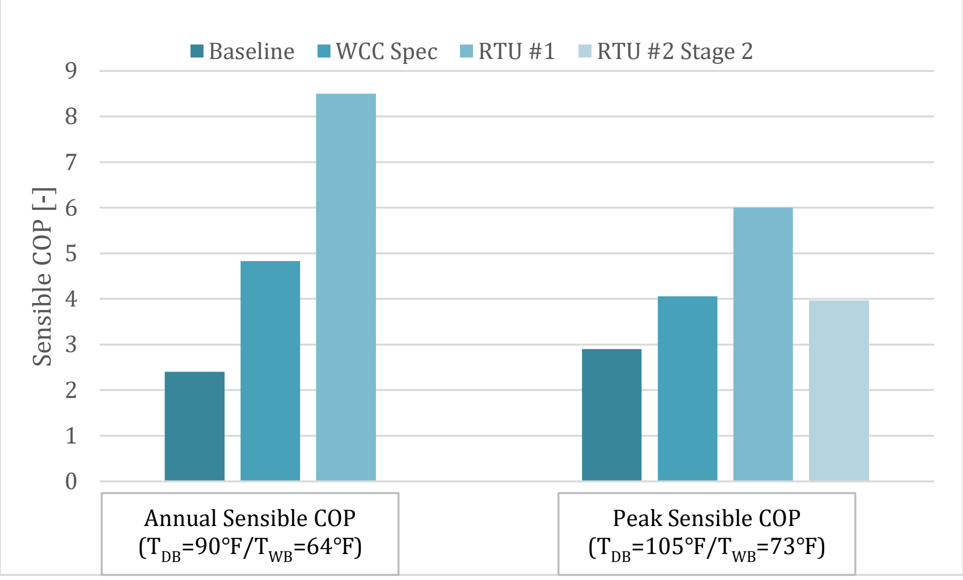

Figure 2: Performance of two Western Cooling Challenge entries relative to WCC specifications and DOE 2010 minimum efficiency baseline equipment (Note: test could not be conduction at annual conditions for RTU#2)

In addition to laboratory testing, the team undertook a series of field tests over several years in order to demonstrate actual performance to potential customers, and to support the development of utility incentives. The detailed test results in different applications and climates for WCC and related technologies have been documented in individual reports, Table 1 attempts to summarize the key findings from these studies, where the first two studies were performed on the two entries tested in the lab, and the other studies were on key components of the evaporative technologies employed within WCC entries.

Table 1. Summary of field studies of WCC equipment and retrofit pre-cooling

Application	Technology	Location	Key Finding	Citation	Sponsor
University Office	WCC Entry #1	Davis, CA	11-25% savings plus extra ventilation	(Woolley and Grupp, 2013)	California Energy Commission

Application	Technology	Location	Key Finding	Citation	Sponsor
Mall Tenant/ Common Areas	WCC Entry #2	Fairfield, CA	Up to 19% energy savings	(Harrington, Woolley, and Davis, 2015)	Pacific Gas & Electric
Cellular Sites	Indirect Evaporative Coolers	CA Climate Zone 8	Sensible COP between 7-19	(Woolley and Mande, 2015)	Southern California Edison
Big-Box Retail Store	Dual Evaporative Pre-cooler	Palmdale, CA	12-72% Increase in COP	(Modera, Woolley and Liu, 2014)	Southern California Edison
Office and Kitchen	Dual Evaporative Pre-cooler	Ontario, CA	20-64% savings	(Woolley, Mande, and Modera, 2014)	Southern California Edison
Dining Facility	Spray Evaporative Pre-Cooler	Marysville, CA	22% savings	(Woolley, Grupp and Fortunato, 2013)	California Energy Commission

In performing these studies along with a market barriers study (SCE EP, 2015), and in discussions with manufacturers, the team realized that: a) introducing new products into the RTU replacement market presents significant logistical and market challenges, (e.g. the commodity nature of many RTUs, and issues with stocking yet another line of RTUs) and b) a significant fraction of the WCC savings could be achieved more quickly by means of retrofits (e.g. adding evaporative pre-coolers to the air entering the condenser and/or the outdoor-air intake). Combining these reasons with the fact that existing RTUs typically have 10-20 years of remaining lifetime on rooftops (Energy and Environmental Analysis. 2005), the team decided to shift its focus towards an RTU retrofit strategy (Modera and Ahmed, 2011).

When shifting to retrofits, although there were several opportunities identified, we needed to start somewhere, and the logical choice was to build upon the results obtained through the field studies on the performance of evaporative pre-coolers for RTU condenser air. These devices use direct evaporative cooling to lower the temperature of the air entering the condenser, thereby increasing RTU capacity and decreasing power draw, resulting in higher COPs. Although the best performance appeared to be achieved by a technology that simultaneously treated ventilation air with indirect evaporative cooling, there was only one manufacturer of that technology, while there are multiple manufacturers of evaporative condenser-air pre-coolers. Having multiple manufacturers of a given product makes the development of incentive programs easier from a product availability perspective, although it introduces the issue of whether all products provide equivalent performance. A more detailed examination of the studies summarized in Table 1 suggests that this is not the case. This led to the next chapter of this journey, which was to develop a means for distinguishing the performance of different technologies.

ASHRAE Standard Development

Third-party testing is by far the preferred means by which utility programs, and customers, would like to make investment decisions. The gold standard is independent third-party testing performed for product alternatives according to the same testing protocol (think Consumer Reports). The team thus decided to pursue the development of an ASHRAE Standard to test the performance of evaporative pre-coolers, in particular condenser-air pre-coolers. . In our case, a group of seven members including utilities and manufacturers was assembled in 2013 to write the Standard, which resulted in a vote to send the complete standard out for Public Review in 2017 (ASHRAE Standard 212P - Method of Test for Determining Energy Performance and Water-Use Efficiency of Add-On Evaporative Pre-Coolers for Unitary Air Conditioning Equipment).The development of the standard is an evolutionary process, having to manage questions that arose about treatment of different technologies, interactions with equipment performance, and appropriate accounting for performance in different applications. The fundamentals of the standard are described in Pistochini, Young and Modera (2013), however some of the key points are described here, as are several evolutionary developments that occurred since 2013.

The standard needed to equitably address different types of precooling technologies on the market, which mostly fall into two categories: a) products that use a media to evaporate the water into the air, and b) products that use sprays to induce evaporation. For example, the performance of the products that use media to evaporate water does not depend upon supply water pressure, whereas spray products do.

In terms of interactions with equipment performance, one issue was how to handle resistance to flow across the condenser coil, and another was how to manage the fact that the response to reductions in condenser inlet temperature vary between RTUs. The former was resolved by including tests of the flow resistance of the products both during standby and during operation. The latter was resolved by measuring the evaporative effectiveness of the products, essentially how closely the exit air from the product approaches the maximum cooling available (i.e. the wet-bulb temperature of the outdoor air), and then applying the cooling associated with the measured evaporative effectiveness to a generic RTU (using generic RTU temperature performance curves). This latter development helped avoid the possibility of a manufacturer overstating their product’s performance by testing with a particularly sensitive RTU.

The issue of variability between different applications was a critical component of this effort. This included issues such as: a) the influence of outdoor air conditions (i.e. temperature and humidity level) on evaporative effectiveness, b) the influence of the design air velocity thru the condenser (i.e. influence of air velocity and residence time in the pre-cooler), and c) the sizing of the evaporative cooler cross-sectional area relative to the cross-sectional area of the condenser (similar to b)). These were managed by measuring performance at multiple temperature/humidity combinations, and at multiple air velocities. Finally, the standard also had to quantify the water use associated with the reported cooling performance.

Interestingly, a number of performance considerations were abandoned over the course of the standard development process, so as to manage the scope of the effort, and to keep the development process from dragging on for too long. Some examples are the measurement of equipment longevity and quantifying the amount of water required to maintain that equipment longevity.

Some examples of what comes out of the proposed ASHRAE standard test procedure are presented in Figures 3 and 4. Figure 3 shows the variability in evaporative effectiveness between different products that were tested, as well as the variability of evaporative effectiveness with the measured wet bulb depression (difference between outdoor air dry bulb temperature and wet bulb temperature). It is clear that the range of performance between products is wide, in this case three pre-coolers are seen to be very close in performance, and two others perform considerably less well. In addition, it appears that the performance of the better pre-coolers is not very sensitive to wet-bulb depression. Perhaps most interestingly, the pre-cooler that currently has the largest market share in California is not in the group of top performers.

Figure 4 shows the impacts of air velocity on the evaporative effectiveness of one particular pre-cooler. As expected, the evaporative effectiveness decreases as the face velocity increases, in this case by 18% when the face velocity is increased from 225 ft/min to 325 ft/min. To put this in perspective, an analysis of published RTU performance data for a major manufacturer showed a range of condenser face velocities between 190 and 650 ft/min.

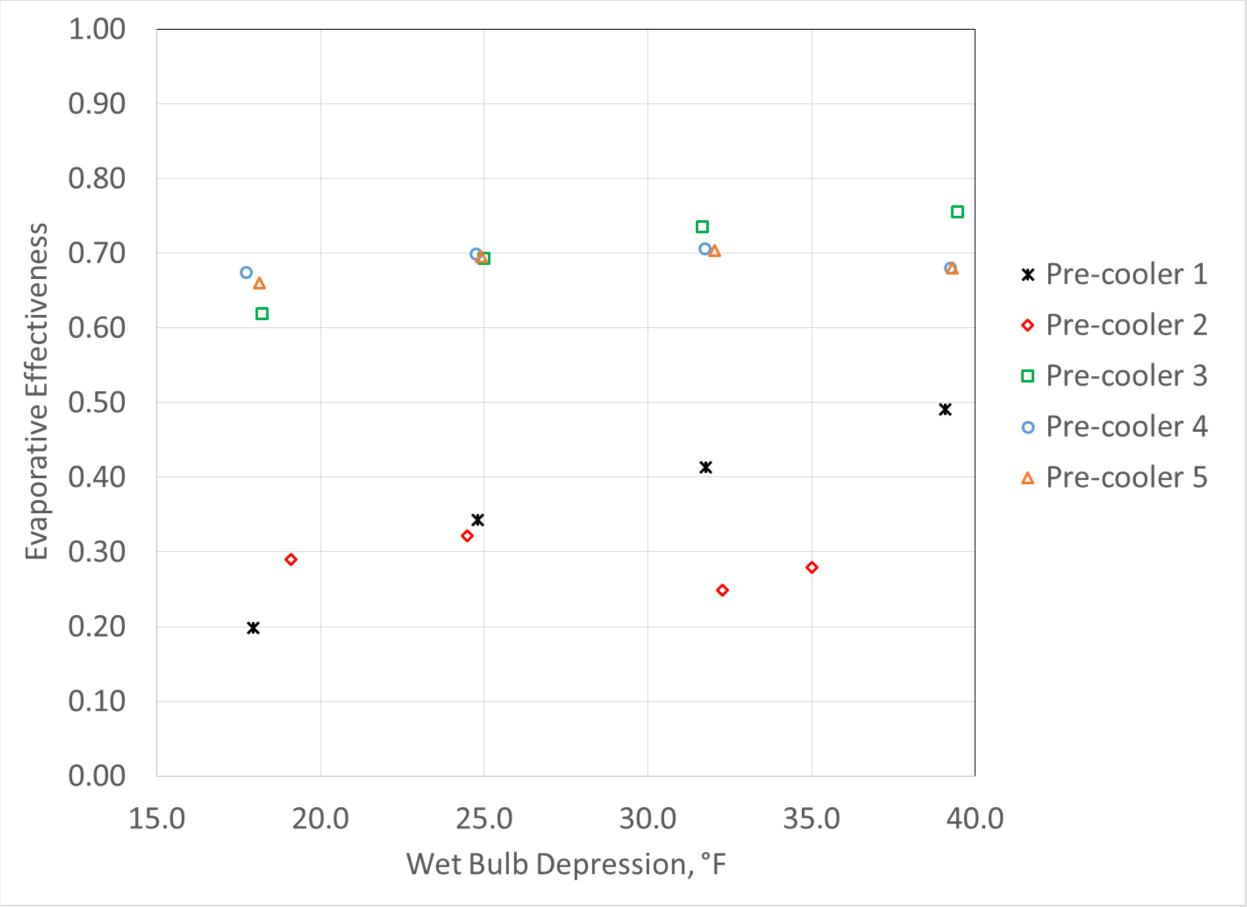

Figure 3: Measured evaporative effectiveness for five different evaporative pre-coolers at different outdoor-air web bulb depressions ($T_{drybulb}$-$T_{wetbulb}$)

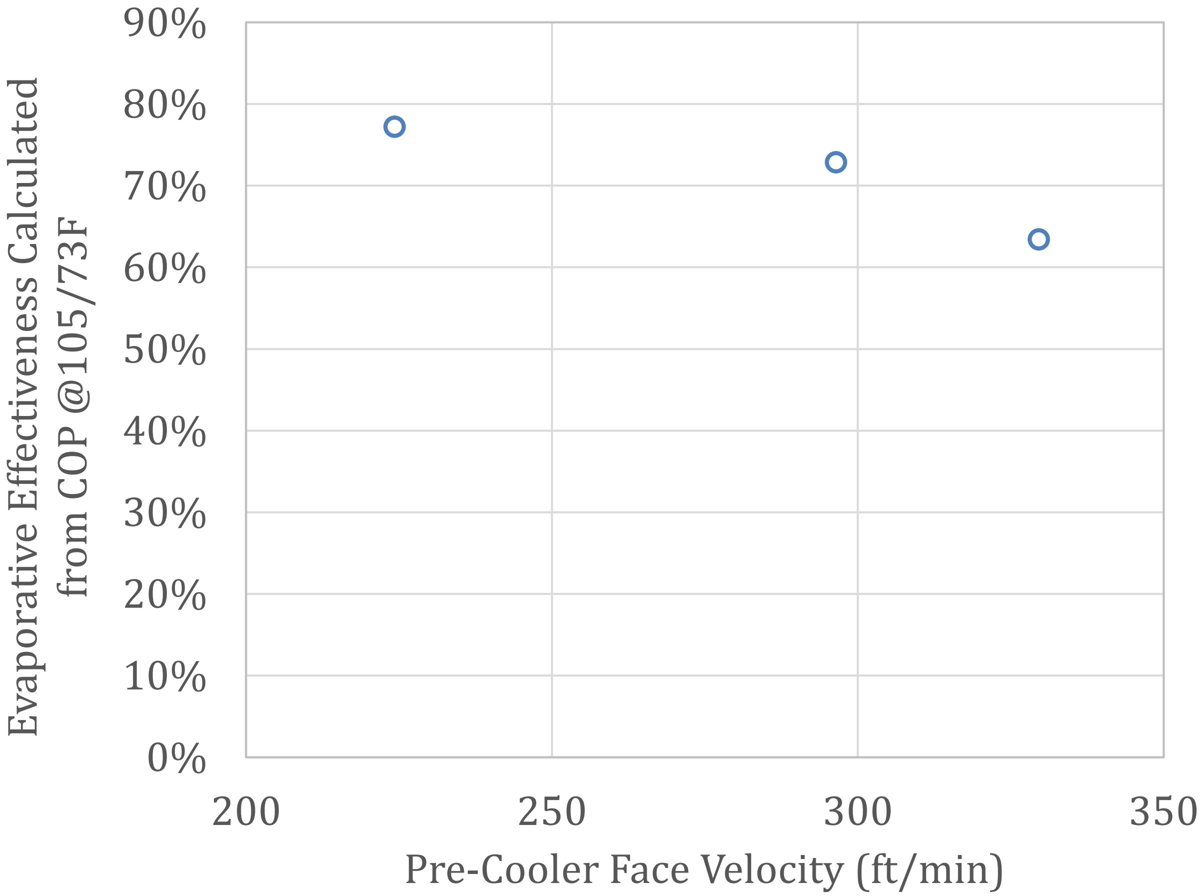

Figure 4: Measured evaporative effectiveness for different face velocities for one evaporative pre-cooler

Discussion

Given all the efforts that have been described herein, it is fair to ask how much traction has been achieved. Although a comprehensive market analysis has not been performed, pre-cooling technology incentives are offered by over 20 California utilities through their custom/calculated incentives programs. As an example, one major pre-cooling manufacturer was recently awarded a contract to reduce commercial building energy use by 72.5 megawatts within Southern California Edison's service territory (Evaporcool Solutions, 2015). Data from another manufacturer indicates that they have done at least 380 evaporative-pre-cooler installations on the roofs of national big-box retail stores. These installations suggest that commercial customers found that even without an incentive, the savings themselves were enough motivation to retrofit their facilities.

This paper has tried to describe a path that was followed to attempt to successfully effect a change in the energy efficiency and peak electrical demand associated with rooftop packaged air conditioners (RTUs) on commercial buildings. One of the lessons learned by the authors was that the time required to put in place everything that is needed to effect a change in standard practice is considerable, at least in the case of a relatively new HVAC technology. Although this is not surprising to anyone who has ever gone through this process, this paper provides a clear chronological case study of the process. Moreover, we also found that the market does not necessarily wait for the process to be completed, as is evidenced by the larger market share that has been reported for a product that does not fall in the group of best-performing products tested during the development of the proposed ASHRAE Standard for testing evaporative pre-cooler performance. It is also worth noting that a larger manufacturer acquired the relatively small company that produced the first entry to the Western Cooling Challenge (WCC), and also acquired the company that produced the high-performing dual-pre-cooling technology that was incorporated into the second WCC entry. Although these acquisitions do not save any energy per se, they do imply some value associated with the technologies associated with the WCC process, and also imply that these technologies will now benefit from the ability for more significant investment, as well as larger, more impactful distribution networks

Concerning next steps, the authors will continue to support utility programs inside and outside California, as well as manufacturers that require testing under the proposed new ASHRAE Method of Test for evaporative pre-coolers.

Conclusions

There are a several conclusions that can be drawn across this multi-year effort that could not have been identified with any single study. First and foremost, this series of studies launched by the WCC makes clear that there are significant electricity and peak demand savings that can be accomplished in RTUs in California without the complete redesign of the RTU. The savings measured in the laboratory were generally confirmed in the field, however the field studies also confirmed that savings can vary considerably depending upon the application, and on the particular version of evaporative pre-cooling being employed. This observation justifies the significant effort devoted to conducting field tests in various applications, particularly because there were no suitable laboratory facilities to test the range of operating conditions that mimic the California climate zones. Similarly, the measured variability between laboratory test results for different products justifies the effort to produce an ASHRAE standard for rating evaporative cooling performance.

Another important conclusion is that the path we chose to make a change in RTU efficiency in California was not an easy one, nor a quick one, and that the possibility of utility incentives was not sufficient by itself to draw the interest of manufacturers. It is however not clear whether there was an easier, quicker way to achieve what we did. The authors experience with introducing other new HVAC technologies suggest that a quick painless pathway is difficult or impossible to find. One other point related to the strategy employed is that, by making use of the ASHRAE Standards pathway, longevity of the process is more likely.

In addition, the authors are comfortable in concluding that significant learning and value was realized by assembling a diverse team of partners in this effort, including utility engineers, manufacturers, customers and university researchers familiar with the ASHRAE Standards process. The authors also conclude that despite manufacturer marketing efforts and vested interest in the success of this technology, the ultimate acceptance of this technology is up to the customer.

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