Evaporative coolers: affordable comfort that's easy on the grid

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Abstract

The calamitous heat wave of the summer of 2003 may be a precursor of the consequences of global warming. In all events, it sparked a new and large demand for air conditioning (A/C) in the residential sector in areas of Europe that have traditionally done without. Compressor-based space cooling can produce comfort, but it is associated with high first cost, substantial energy bills, and bothersome noise. Most important from the societal perspective, air conditioning loads on hot summer days threaten to cause unprecedented peak demand problems for European electric grids. Modern evaporative coolers produce good thermal comfort at lower first costs. Except under conditions of high relative humidity, comfort is better than with compressor-based A/C because with evaporative cooling, high volumes of fresh air are circulated into conditioned spaces. Both compressor-based A/C and evaporative cooling systems are becoming more efficient, but on a unit-of-cooling-per-kWh-of-electricity basis, evaporative cooling is at least four times more efficient than A/C and demand is less by a factor of five or more.

This paper examines:

- New technologies and trends in upgrading existing technologies in evaporative cooling—direct, indirect, and indirect/direct;
- Climate zones in Europe that favor evaporative cooling (most do);
- The cost-effectiveness of evaporative cooling versus compressor-based cooling for new and retrofit residential applications from the perspectives of both end users and utility systems; and
- Policy and program options for promoting evaporative cooling systems and related energy-efficiency measures tailored to the European community.

Water use by evaporative coolers is quite moderate, typically less than the amount of water that can be saved by the installation of a low-flow shower head or a water-conserving toilet. In addition, water use at the power plant is less by a factor of 5 than that required to generate additional electricity for a conventional A/C unit.

Introduction

Evaporative coolers have lost market share for cooling buildings in the western US because older style units have earned a reputation for poor performance. However, there's a world of difference between old-style swamp coolers and modern evaporative cooling systems. The former are cheap, require regular maintenance, have low efficiency, and waste water The latter can provide years of trouble-free service and cool fresh air at a lower energy cost than convention air conditioners – and with lower initial costs. In addition, the latest evaporative cooler designs are easier on the grid than are compressor-based cooling systems. Instead of peak demands of three to five kilowatts (kW) or more, typical demands for mid-size evaporative coolers suitable for residential use are well less than one kW. In addition to improved performance, modern evaporative coolers include options

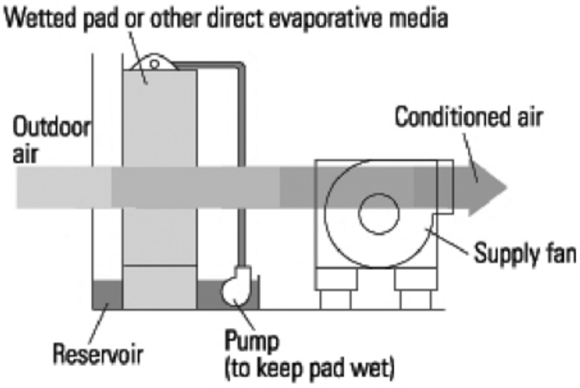

Figure 1. *Direct evaporative cooler*
Source: Platts

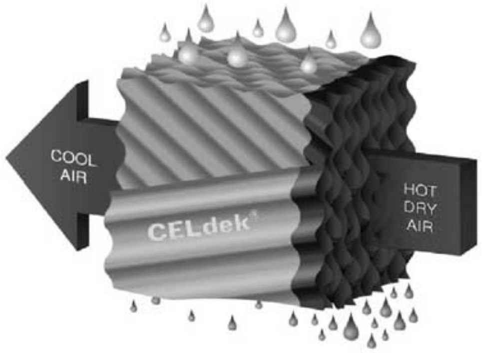

Figure 2. *Modern evaporative cooling media*
Source: Munters

for thermostatic control and automated flushing of reservoir water to reduce buildup of impurities. Accordingly, widespread use of evaporative coolers can help delay adding expensive new power plants to the electric grid and the controversial transmission lines that can accompany them

HOW EVAPORATIVE COOLING WORKS

When air blows through a wet medium—a tee shirt, aspen fibers (excelsior), or treated cellulose, fiberglass, or plastic—some of the water is transferred to the air and its dry bulb temperature is lowered. The cooling effect depends on the temperature difference between dry and wet bulb temperatures, the pathway and velocity of the air, and the quality and condition of the wet medium.

Dry bulb and wet bulb temperature: The temperature of air measured with a thermometer whose sensing element is dry is known as "dry bulb temperature." If a thermometer's sensing element is surrounded by a wet wick over which air is blown, the sensor is evaporatively cooled to its "wet bulb" temperature. When the relative humidity is at 100%, there is no difference between dry and wet bulb temperatures, but as the relative humidity of the air drops, so does the wet bulb temperature with respect to dry bulb temperature. In climates where humidity is relatively low in the summer, the differences are substantial. For example, at 10 percent relative humidity and a dry bulb temperature of 32ºC, the wet bulb temperature is 14ºC, an 18 degree difference. This is often called the "depression" of wet bulb below dry bulb. Climates with large depressions favor evaporative cooling techniques.

TYPES OF EVAPORATIVE COOLERS

"Direct" evaporative coolers use a fan to pull outside air through media (pads) that are kept thoroughly wet by water that is sprayed or dripped on them (Figures 1 and 2). This both filters the air and cools it. Lower speeds give more exposure time to the wetted media, thereby achieving more cooling. Media for evaporative coolers has to be efficient, which means that it must allow for as much cooling as temperature conditions allow while minimizing pressure drop, thereby saving fan power. Well-designed media filters the air stream, but is also self-cleaning, in that water dripping across it to the sump below performs a cleaning function. The water is typically delivered via tubes from a small pump which draws from a reservoir below. The reservoir is replenished with tap water whose level is controlled by a float valve. The resulting fresh, cool, humidified air is blown into buildings where the pattern of flow (and cool air delivered) is determined by the location and extent of openings in the conditioned envelope such as windows or special dedicated ducts, including "up-ducts" in the attic floor. These are effectively back-draft dampers which open when the home is pressurized by the evaporative cooler blower, thereby controlling the distribution of cooling air without the need for opening windows. Air is exhausted from attic vents.

Ample ducting through windows or other pathways is very important in controlling cooling distribution and in keeping indoor humidity levels at reasonable levels. In practice maintaining homes at 40 to 50% relative humidity is easily achieved except when the relative humidity of exterior air is exceptionally high.

Modern evaporative coolers couple high-performance media with low-velocity air flow. They maximize moisture transfer as the air traverses the media to enhance "direct saturation effectiveness," which is analogous to cooling efficiency. Direct evaporative cooler performance is measured relative to the wet bulb depression. Well-designed systems with thick (25 to 30 centimeters or more) media operating properly can achieve 93% effectiveness, whereas older style systems that typically use 5 centimeter thick excelsior may achieve effectiveness of 50% to at most 80%. Although these older-technology units are less expensive, they produce less comfort, waste water, waste energy, and require more frequent maintenance, particularly in replacement of media, whose lifetimes are six to ten times shorter than those of high performance media. Accordingly, I do not recommend their use.

Indirect evaporative coolers take advantage of evaporative cooling effects, but cool without raising indoor humidity. Figure 3 shows a common configuration of indirect cooling that makes use of an air-to-air heat exchanger. The main fan supplies outside air through the dry passages of a heat exchanger into the dwelling, while a secondary fan delivers exhaust air from the dwelling, fresh air, or some combination through wetted passages in thermal contact with the dry passages of the heat exchanger. A variation, called "indirect/direct," adds a second stage of direct evaporative cooling before the conditioned air enters the dwelling to further lower the temperature of the incoming air. Efficient indirect/direct units can deliver air that is cooler than the outside wet bulb temperature.

Table 1 shows delivery temperature at 85% saturation effectiveness (corresponding to a good-quality direct cooler) and delivery temperature at 105% (corresponding to a good quality indirect/direct two stage evaporative cooler for selected European cities whose climates favor evaporative cooling.) The performance figures shown are for ambient temperature circumstances that occur only 1 percent of the time in the selected cities. When ambient temperatures are lower than those shown, delivery temperatures are lower than those shown in the table, providing more comfort per unit of energy used. Weather regions with 1% wet bulb temperatures of 21ºC or below can be comfortably cooled with direct evaporative coolers, and those with 1% wet bulb temperatures of up to 24ºC can be made comfortable for many people, particularly with direct/indirect coolers. Note that Rome is a close call.

Under the dry and wet bulb circumstances shown in the table, indoor relative humidity is typically 40% to 50%. It is important to have adequate openings for exhaust air, either windows or dedicated exhaust louvers, to keep indoor relative humidity in check and to provide a continuous stream of cooled air through areas of the home one desires to be particularly comfortable.

WATER AND ENERGY ISSUES

Evaporating a liter of water yields about 0.68 kWh of cooling, most of which contributes to cooling the air stream in a well-designed evaporative cooler. Water is used to thoroughly wet a medium in the air stream, which tends to dry the medium and cool the air. Ideally, if the flow of water and the flow of air are well matched in a carefully-designed evaporative cooler, the air is cooled efficiently and most of the water is evaporated. However, some extra water is important to flush the residue of air pollutants and scale in the water. In inefficient units, water that is not evaporated by the cooler is continuously diluted by make-up water in the reservoir (sump), the residue going down an overflow drain. This "bleed" system continuously dilutes the water and reduces the concentration of scale and impurities, but this method of cleaning wastes water.

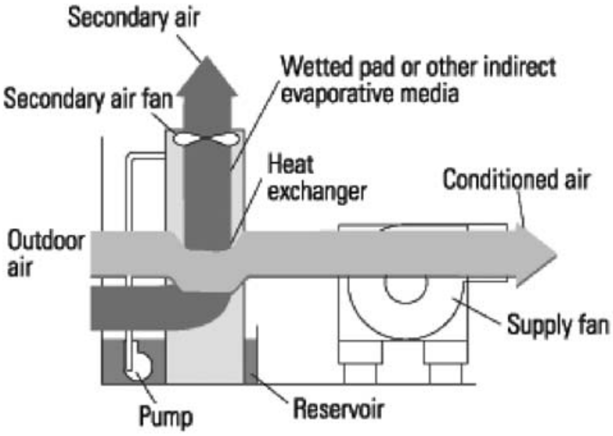

Figure 3. *Indirect evaporative cooling. Secondary air, which is at ambient temperature, passes through a wetted pad then through the heat exchanger before being exhausted outside. Conditioned air is cooled in the heat exchanger without picking up humidity, then is cooled a second time by direct evaporative means, where it does pick up humidity.*
Source: Platts

Higher-quality units use a more effective and less wasteful batch process to deal with impurities. With this system of periodic purging, almost all of the water is used to provide cooling. The sump is typically sloped so that heavier pollutants and scale tend to collect at the bottom. Instead of continuous dilution, after an elapsed running time of cooler operation of several hours, the reservoir is drained and flushed automatically. The residue of several gallons from this "sump dump" may be piped to a nearby garden. The discharged portion is well matched to the needs of a garden – more water is delivered on hot days when the evaporative cooler works the most and plants are especially thirsty.

Table 1. Delivery temperatures for selected European cities at 1% dry bulb. During 99 percent of the typical cooling season, ambient temperatures (and delivery temperatures) are lower than those shown.

City	Dry bulb ambient temp (ºC)	Wet bulb ambient temp (ºC)	Relative Humidity (%)	Depression (ºC)	Temp delivered @ 85% effectiveness (ºC) (High Performance Direct)	Temp delivered @ 105% effectiveness (ºC) (Direct/Indirect)
Athens	32.8	20.0	34	12.8	21.9	19.4
Berlin	27.8	18.3	40	9.4	19.8	17.9
Heidelberg	30.0	19.4	38	10.6	21.0	18.9
Madrid	34.4	20.0	28	14.4	22.2	19.3
Paris	27.8	19.4	50	8.3	20.7	19.0
Rome	30.0	23.3	58	6.7	24.3	23.0
Strasbourg	28.9	20.0	46	8.9	21.3	19.6
Zurich	26.7	18.3	45	8.3	19.6	17.9

Source: Calculations from manufacturers' performance data, AdobeAir, Inc, Phoenix Manufacturing, Inc, Speakman CRS

Table 2. Characteristics of dwelling modeled.

Parameter	Units
Dwelling Size	142 m^2
Ceiling Height	2.7 m
Windows	16 wood frame double pane windows of 1.125 m^2 each, 4 on each façade, R = 0.37, Solar heat gain coefficient = 0.5
Ceiling R	3.3
Walls R	2.2
Infiltration	Effective Leakage Area = 645 cm^2
HVAC Cooling Efficiency	COP = 2.6
Summer Set Point	25 C

Table 3. Energy and water use and savings in selected EU cities. "DX" is direct expansion compressor-based A/C.

City	Cooling energy DX (kWh/yr)	Cooling energy evap (kWh/yr)	Annual savings (kWh/yr)	DX source water Use (l/yr)	Evap source water use (l/yr)	Water savings at source (l/yr)	Evap water use at site (l/yr)	Net evap water use (l/yr)
Athens	4 107	821	3,286	6 982	1 396	5 586	16 221	10 635
Berlin	768	154	614	1 305	261	1 044	3 050	2 006
Madrid	2 808	562	2 246	4 774	955	3 819	10 980	7 161
Paris	706	141	565	1 201	240	961	2 816	1 855
Rome	3 063	613	2 451	5 208	1 042	4 166	12 150	7 984
Strasbourg	1 117	223	893	1 899	380	1 519	4 431	2 912
Zurich	701	140	561	1 192	238	954	2 753	1 799

Table 4. Cost comparison of conventional compressor-based cooling and evaporative cooling.

City	Elec Cost (Euro/kWh)	DX A/C annual cooling costs (Euro/yr)	Evap Annual cooling costs (Euro/yr)	Annual savings (Euro/yr)
Athens	0.11	452	90	361
Berlin	0.14	107	21	86
Madrid	0.11	309	62	247
Paris	0.14	99	20	79
Rome	0.2	613	123	490
Strasbourg	0.14	156	31	125
Zurich	0.14	98	20	79
Averages	0.14	262	52	210

While an evaporative cooler does consume a significant amount of water, it also saves water consumed at the power plant (assuming that a compressor-based air conditioner would be used for cooling if the evaporative cooler were not used). Generating a kWh of electricity with a thermoelectric plant uses about 1.7 liters of water per kWh generated, according to a detailed study by scientists at the National Renewable Energy Laboratory in the U.S. (Torcellini *et al*, 2003). Since conventional compressor-based air conditioning systems use substantially more energy than do evaporative coolers, water use at the power plant (source) is proportionally greater.

Simulations were conducted using Energy 10 hour-by-hour energy analytic software. The homes modeled are 142 m^2 structures whose principal characteristics are shown in Table 2. Table 3 summarizes performance.

According to this analysis, modern residential evaporative coolers in the selected EU area cities use an average of 7 486 liters of water per year at the site, ranging from 2 753 liters in Zurich to 16 211 in Athens. This amount of water use represents on the order of 5% of annual water use per household. However, from the overall environmental point of view that takes into account water used at the power station, net water use averages 4 907 liters of water per year. Energy savings versus conventional compressor-based direct expansion cooling average 80 percent, and demand savings exceed that figure, especially with particularly efficient models which have electronically commutated motors (see below.)

An examination of operating cost figures is shown in Table 4. This shows annual cost to the end user of cooling moderately efficient 142 m^2 homes in the seven cities illustrated electricity rates applicable to single family residences in each city in July of 2004 were used to estimate costs. The cost of water is not included in this calculation, although in an analogous study by the author in hot areas of the US, the annual cost of extra water ranged from 4 Euro in Denver, Colorado to 15 Euro in Phoenix, Arizona, with an average in the Southwestern US of 9 Euro.

First Costs

First costs of cooling equipment tend to be a function of its efficiency, whether the systems are conventional or evaporative coolers. In the case of conventional A/C units, split systems tend to have larger market shares than do packaged systems. Average costs are around 1 200 Euro for A/C equipment and 2 250 Euro for installed costs. Smaller packaged and through-the-wall units cost substantially less, on the order of 400 Euro depending on output ratings.

The equipment for single-stage evaporative cooling systems with a saturation effectiveness of greater than 80% under all operating conditions, variable (or at least two) speed motors, and a sump-dump feature for effective cleaning with minimal water use, range in cost from 400 Euro to 850 Euro, depending on saturation effectiveness and blower horsepower. Blower horsepower is the principal determining factor in air flow rates. Equipment for two-stage (indirect/direct) evaporative coolers whose saturation effectiveness is in the 105% to 110% range is 1 200 Euro to slightly less than 2 200 Euro. Installation costs are lower than they are for central air conditioning systems in large measure because of substantially simplified ducting. Installations on a concrete pad next to a home run from 400 Euro to 750 Euro while attic installations run from 600 Euro to 1 000 Euro, depending on the number of up-ducts that must be installed and other factors like access to plumbing and electricity. Considering these cost ranges, the total installed cost for an efficient single-stage evaporative cooling system is typically between 1 200 Euro to 1 600 Euro. The total installed cost for an efficient two-stage evaporative cooler is on the order of 1 900 Euro to 2 600 Euro. In general, installed costs of efficient evaporative equipment are lower than installed costs for comparable compressor-based central cooling systems.

Choosing Efficiency

As with conventional air conditioning systems, evaporative coolers that deliver more cooling cost more to purchase, more to operate, and make more noise (because they must move more air.) To optimize economic and energy performance, as well as to maximize comfort, it is best to ensure that the home's envelope is well insulated, that windows have low solar heating gain coefficients (SHGC), and that effective exterior shading devices (overhangs, fins, shutters, louvers, strategically-located vegetation) are employed to block direct beam sunshine during the cooling season. These strategies lower the cooling load and enable smaller, less-expensive cooling equipment.

In general, low-end, direct systems which use only several inches of media (that must be replaced frequently) are inefficient and waste water. Although their low cost makes them attractive for some uses, they are generally a bad choice for the long term. Better by far are single-inlet systems with thick media resulting in saturation effectiveness of at least 80% under all operating conditions, variable speed motors, a sump-dump feature for effective cleaning with minimal water use, and thermostatic controls.

Indirect/direct evaporative coolers can achieve comfort in a wider range of climate zones—those that are both hotter and have higher humidities—than can direct machines since they are capable of delivering air that is several degrees below wet bulb temperature.

Speakman CRS (for "Clean, Renewable, Sustainable") is a branch of the Speakman Company, a Delaware firm that has been producing shower heads and other water-related products for more than 130 years. The company is a newcomer to the evaporative cooler field, but is now manufacturing and distributing a newly-modified indirect/direct evaporative cooler called the OASys, which was developed by the Davis Energy Group in Davis, California.

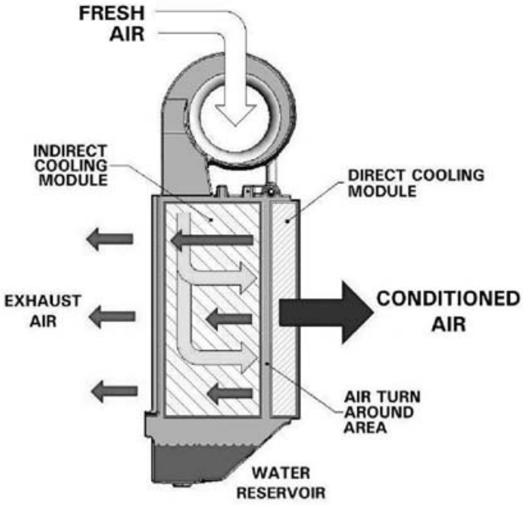

Figure 4. OASys air flow
Source: Davis Energy Group

As shown in Figure 4, the system uses a single blower that pulls in outside air and directs most of it through the dry side of a heat exchanger that uses 36 cm thick media to efficiently indirectly cool the air stream without adding moisture. This partially-cooled air then passes through a direct cooling module before being directed into the home. About 27 percent of the outside air stream is used in the other (wet) side of the counter-flow heat exchanger, where it is cooled, gathers moisture, and then is discharged to the outdoors. Water from both the indirect and direct cooling processes gathers in a single reservoir where it is purged with a frequency reflective of the amount of scale in local tap water and the rate of water use by the system (which depends on the blower speed that is controlled by a thermostat).

This machine incorporates a number of improvements over earlier indirect/direct evaporative coolers designed for residential use. It employs a single polyethylene cabinet that houses all parts of the system. This substantially simplifies the overall design, helps maintain tolerances, shortens assembly time, and ensures a long lifetime. The OASys also uses an electronically-commutated motor (ECM) controlled by a smart thermostat, so blower speed can be changed while maintaining high efficiency at all speeds.

Figure 5 shows how system efficiency varies with fan speed. The data gathered was at entering dry bulb temperatures of 40ºC, with the unit supplying dry bulb temperatures of 20ºC. The y-axis shows cooling energy delivered per unit of electric energy input, analogous to energy efficiency rating (EER) for a conventional A/C, in this case at a design temperature of 40ºC. The power term is the sum of fan and pump power.

Engineers at the Davis Energy Group took these and other test results and performed simulations of a very efficient

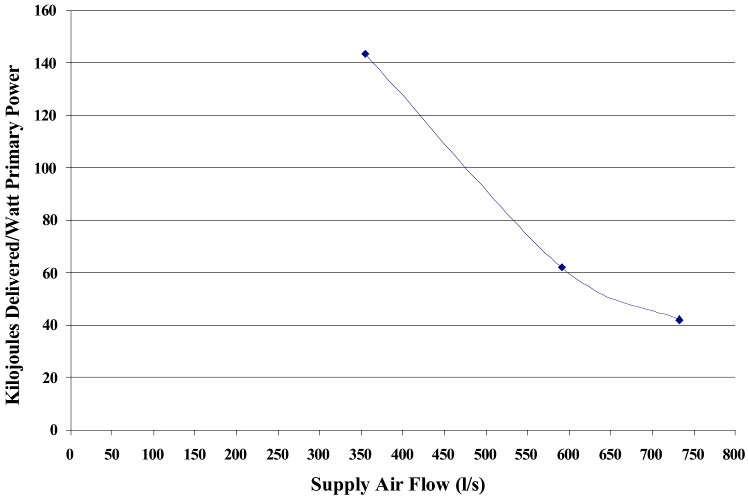

Figure 5. *OASis measured performance at three supply air flow rates. All evaporative coolers exhibit increased efficiency at lower fan speeds, so when operating close to desired indoor air temperatures, it is best to slow down the fan speed.*
Sources: Davis Energy Group; Lawrence Berkeley National Laboratory

150 square meter home in eight of California's climate zones. It is useful to examine the results for Fresno, which has a hot climate not unlike many locations in southern portions of the EU (1% dry bulb temp 38ºC, wet bulb 21ºC). The base-case home with a conventional compressor-based air conditioning system rated at 12 SEER uses 1 886 kWh/yr with a peak of 3 kW, while the OASys uses 135 kWh/yr with a peak of 0.52 kW. This amounts to an annual energy savings of 93% and a peak demand savings of 83%. Simulation results reflect a thermostat setting of 27ºC for the conventionally air conditioned home, but 26ºC for the evaporatively cooled home to compensate for higher indoor humidity in the latter case.

The Market

This kind of savings points the way to potentially very cost-effective use of energy-efficient evaporative cooling systems in new home construction as well as retrofit in those regions in which 99 percent of the time wet bulb temperatures are 22ºC or below. Yet the disturbing market trend is toward using more compressor-based air conditioning.

The greatest barriers to acceptance of the newly-improved evaporative cooling technology appear to be misperceptions based on the performance of old technology and the lack of awareness on the part of the buying public – and the builders who serve them. For the vast majority of the public – and the building profession – evaporative cooling means unsightly, low-tech, and often poorly-performing swamp coolers that waste water. With modern coolers, none of these shortcomings hold. However, a major education and awareness-building effort is needed to convince homeowners, builders, and retrofitters that evaporative cooling can be a high-performance alternative to conventional air conditioning systems – it is potentially much less costly over its lifetime, and can be designed to be at least as comfortable as the alternative.

Conclusions and Recommendations

Owing to recent hotter summers and the perceived strong likelihood of global warming, many homes which have not been air conditioned are adding conventional compressor-based air conditioning. Although evaporative coolers are not widely used in Europe, this paper has demonstrated via hourly simulations that modern, efficient evaporative coolers can indeed supply cooling needs in the majority of European climates areas at substantially lower costs. Energy use is less by a factor or four and cost savings average over 200 Euro per year for average new homes in the seven cities examined. Perhaps most important from the standpoint of public policy, the demand on the electric grid of evaporative coolers is on the order of five times less than is the demand of conventional cooling systems. Since cooling demand is at a peak on hot summer weekday afternoon in southern European areas, this should be a critical consideration by utility planners in the face of global warming trends.

Utility companies and governments in the EU can play an important role not only in publicizing their advantages both to the public at large and to the building and retrofit communities but also in providing cash incentives for the purchase of high-efficiency evaporative coolers. Forming partnerships between utility companies and builders to construct model homes that illustrate the advantages of evaporative cooling can help establish the credibility of modern evaporative cooler systems appropriately integrated into a well-designed home.

Building (or retrofitting) a tight, well-insulated model home with careful attention to fenestration (shading, appropriate solar heat gain coefficients versus orientation) is fundamental, of course, as are techniques which both reflect and reradiate sunlight striking the roof. Installing a high-quality evaporative cooler in the attic (or at the side of a home, as with Adobe's new product, Figure 6) in conjunction with well-insulated up-ducts and intelligent controls will meet the cooling needs of the home quite comfortably. Then the home could be heated via a hydronic system, optimally via a radiantly-heated slab, a system which is becoming less costly and is quite reliable. A solar hot water system could supply domestic hot water as well as a substantial portion of the low-temperature needs of the hydronic heating system in the sunny Southwestern climates, with back-up from an efficient, tankless boiler. The result would eliminate conventional duct systems with their associated economic and energy inefficiencies and achieve excellent overall cost effectiveness—as well as health, safety, and comfort.

Concerning the evaporative cooler systems themselves, there is a need on the part of designers, builders, and retrofitters to *think* of them as systems thoroughly integrated into energy-efficient structures. Techniques for sealing them carefully and simply during seasons when cooling is not needed coupled with ensuring that there is no risk of freezing need to be developed. Up-ducts should be thoroughly insulated and positively sealed during times when cooling is not needed and optimized to ensure good distribution of

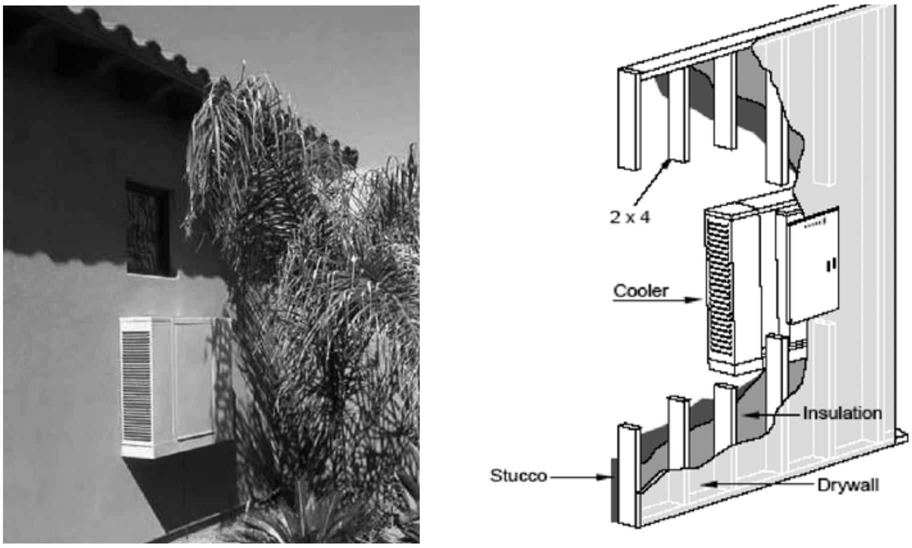

Figure 6. *Master Cool® Slim Wall™ from Adobe*

cooling air. Further, controls need to be developed which not only vary fan speeds and control water cleaning cycles, but also monitor efficiency performance to signal the need for maintenance. Finally, there is room for improvement in the heat exchanger technology used in indirect cooling systems, and several companies are working to develop more efficient systems which require less pressure drop across indirect media while achieving more effective cooling.

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