# Peak Power Reduction Potential for Radiant Cooling Systems

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A significant amount of electrical energy used to cool non-residential buildings is drawn by the fans used to transport the cool air through the thermal distribution system. Separating the ventilation and the thermal conditioning of the building allows reduction of the amount of air transported through the building, if the thermal distribution is provided hydronically. Due to the physical properties of water, hydronic distribution systems can transport a given amount of thermal energy using less than 5% of the otherwise necessary fan energy. The savings of transport energy alone significantly reduces the energy consumption, and especially the peak power requirement. The removal of the building's cooling load is mainly due to radiation, using cooled building components as heat exchanger. This paper shows the advantages of radiant cooling in combination with hydronic thermal distribution systems when compared with All-Air-Systems commonly used in the United States.

## Introduction

Cooling Californian non-residential buildings contributes significantly to the electrical power consumption (in 1985 approximately 9000 GWh) and the peak power demand (in 1989 approximately 6.5 GW). A large amount of electrical energy used to cool buildings is drawn by fans used to transport cool air through the ducts. Part of this electricity used to move the air is heating the conditioned air, and therefore, is part of the internal thermal cooling peak load. Typical thermal cooling peak load for Californian office buildings can be broken down as follows: 31% for lighting, 13% for people, 14% for air transport, and 6% for equipment. External loads account for only 36% of the thermal cooling peak load (Usibelli, Greenberg, Meal, Mitchell, Johnson 1985).

DOE-2 simulations for different California climates using the California Energy Commission (CEC) base case office building show that at peak load, only 10% to 20% of the supply air is outside air (Feustel 1989). This is this fraction of supply air necessary to properly ventilate the buildings to maintain a high level of indoor air quality.

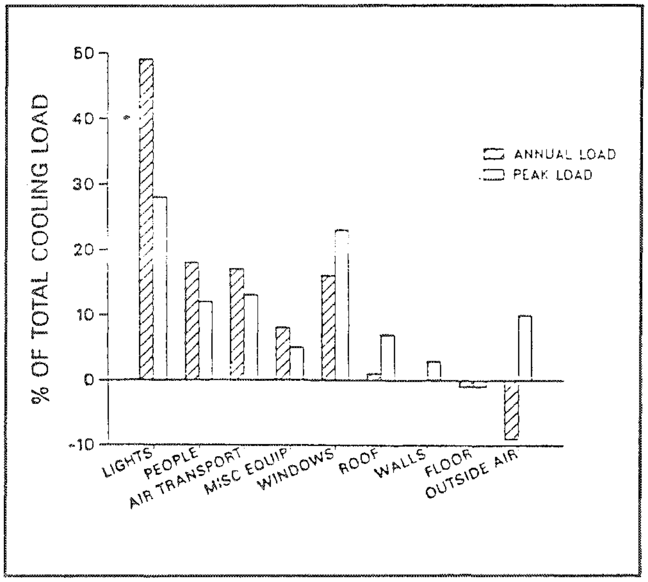

*Figure 1. Cooling Load Components, Typical Office Building, Los Angeles (Usibelli et al.)*

HVAC-systems are designed to maintain indoor air quality, remove pollutants from sources inside the building, and provide thermal space conditioning. Traditionally, HVAC-systems are designed as All-Air-Systems, which means, that air is used to perform all three tasks. All-Air-Systems have been designed as central/decentralized systems, single/dual-path systems, constant/variable volume systems, and low/high velocity systems. For conventional HVAC-systems the difference in volume between supply air and outside air is made up by recirculated air. The recirculated air is necessary to keep the temperature difference between supply air and room air in the comfort range. The additional amount of supply air,however, often causes draft and indoor air quality problems by equally distributing pollutants throughout the building.

Air-and-Water-Systems separate the tasks of ventilation and thermal space conditioning by using a primary air distribution system to fulfill the ventilation requirements and a secondary water distribution system for thermally conditioning the space. These systems reduce the amount of air transported through buildings by 80 to 90%; the cooling is provided mainly by radiation using water as the transport medium. The ventilation has to be provided by a separate outdoor air systems without the recirculating air fraction. This not only improves comfort conditions, but also increases indoor air quality and improves the control and zoning of the system. Due to the physical properties of water, hydronic cooling systems can remove a given amount of thermal energy using less than 5% of the otherwise necessary fan energy.

Since large surfaces are utilized for the heat exchange in hydronic cooling systems (ceilings are most often used), the coolant temperature is only slightly lower than the room temperature. This small temperature difference allows the use of either chillers with high COP-values or a cooling tower to further reduce the electrical power requirements. Additionally, hydronic cooling systems reduce problems caused by duct leakage because the supply air volume is reduced and only conditioned to meet room temperature conditions rather than cooling air temperature conditions. Furthermore, space needs for ventilation systems and their duct work are reduced to about 20% of their original space requirements. Besides the reduction of space requirements for the shafts that house the vertical air distribution system, floor-to-floor height can be reduced, which offsets the initial cost of the additional system. An integration between water distribution lines for hydronic cooling systems and the sprinkler system would further reduce the initial cost.

The thermal storage capacity of the coolant further helps to shift the peak to later hours. Because of the hydronic energy transport, the system has a potential to interact together with thermal energy storage systems (TES) and looped heat pump systems.

# Cooling Applications

## History

Hydronic cooling was in use long before All-Air-Systems were invented. Hauptmann from the University of Heidelberg recently discovered the ruins of a village in Turkey which dates back to 7000 B.C. (Hoelzen 1991). Houses in this village with the Kurdish name Nevala Cori already utilized hydronic cooling by using water supplied by the Kantara Creek. The water was re-routed from the river bed through channels imbedded into the buildings' slab to cool the stone floors.

The use of hydronic cooling in more modern buildings has been investigated more than five decades ago. The earliest technical papers found in our literature survey date back to 1938 (Hottinger 1938; Bradtke 1938). At this time the idea of hydronic systems was not developed further. In 1951, Bilden (1951) reported about the advantages of hydronic heating and cooling and describes some demonstration projects. The cooling effect still was more a by-product of hydronic panel heating systems rather than the target itself. However, Bilden refers to hydronic cooling systems which had been installed in an office building in Paris, a department store in Zuerich, the Museum for Modern Art in Paris, the Hotel Excelsior in Rome, the Banque de Rome and the Palais des Journaux, both in Milan. The combination of hydronic cooling and ventilation is also mentioned in his paper.

The physiological effects of hydronic cooling were addressed in 1957 (Ronge and Lofstedt 1957). They were especially interested in the draft sensation of cold ceilings and the compensation with higher room air temperatures. This led to a comfort chart which shows the interrelation between ceiling surface temperature and the air temperature. The advantages of hydronic heating and cooling, based on the heat exchange of the human body with the environment and remarked, that the heat transfer due to radiation has not been given adequate consideration are described by another publication (Baker 1960). The more comfortable, healthful and more invigorating environment, more uniform air temperatures, cleaner surfaces, neater appearance, and improved efficiency are listed as advantages of panel systems. Condensation might be a problem if an auxiliary dehumidifying coil is not used to control the rooms dew point temperature. Although, cost of operating a cooling panel is less than that of a conventional convection system, the degree of comfort seemed to be more important to Baker.

A contribution to an ASHRAE symposium in the early sixties shows that radiant panel systems have dynamic behavior similar to All-Air-Systems (Boyar 1963). Since then, radiant panel ceilings have been increasingly applied as terminal heating and cooling devices in various types of buildings (Obrecht, Salinger and LaVanture 1973). The authors suggest selecting a slightly higher summer design temperature and a somewhat lower design relative humidity than for conventional All-Air-Systems in order to benefit from the lower mean radiant temperature, which allows higher room air temperatures and still provides the same degree of comfort. Since heat removal from the space is a function of the temperature difference between the water and the room (air and surface temperatures), the design relative humidity and dew point should be selected as low as economically feasible. The supply water temperature is usually 0.5 K higher than the design dew point and a temperature rise of 2 to 4 K throughout the system is used. This usually leads to a temperature difference of approximately 10 K between the design dry-bulb temperature and the mean water temperature.

Although many authors have reported significant advantages of hydronic cooling over All-Air-Systems, not even the two energy crises seemed to have had an effect on the development and the use of hydronic cooling systems.

## Current Development

During the last decade, the attitude of occupants became more critical towards air conditioning systems. Terms like complaint buildings and sick buildings were born. Several publications dealing with occupant satisfaction of air-conditioned and natural ventilated buildings came to the conclusion, that the number of unsatisfied occupants in air-conditioned buildings is significantly higher than in natural ventilated buildings (Kroeling 1985; Fanger 1990; Mandell and Smith 1990). There are still air-conditioning systems which do not produce the required standard of comfort. "The existence of air-conditioning systems is actually only noticed when it is not functioning properly" (Esdorn, Knabl and Kuelpmann 1987).

Draft is a serious problem in many air-conditioned buildings. Air from HVAC-systems is normally turbulent in the occupied zone, and therefore, even small air velocities cause an unwanted local cooling of the human body (Mayer 1988). In order to be able to extract cooling loads from a building, either the amount of cooled air must exceed that of the necessary outdoor air used for ventilation (recirculating air system) or the temperature difference between the supply air and the room air has to be very large, which makes even distribution of supply air in the occupied zone a problem (cold air distribution systems).

Whereas the use of recirculated air might cause draft and/or indoor air quality problems due to the even distribution of the polluted return air, cold air distribution systems can cause very cold local drafts if imperfect mixing between supply air and room air occurs at the air outlet. Both cases will cause comfort problems. Because of comfort problems and the excessive use of transport energy for All-Air-Systems new ventilation strategies were developed (Keller 1988), the foremost being displacement ventilation.[1]

The idea of displacement ventilation is to overcome the problems of mixing ventilation systems. Contaminants are displaced from the breathing zone and clean air is directly supplied with air flow of low turbulent intensity to the breathing zone (Skaret 1987). Displacement ventilation will always result in increased air temperature with height. An upward displacing direction is most efficient for cooling purposes. The heat sources in the room are the driving forces of the vertical air transport by creating convective air currents (plumes). This air flow pattern results in greatly improved ventilation efficiency (for definition of ventilation efficiency, see Sutcliff 1990). Ventilation systems with high ventilation efficiencies use solely outdoor air and, therefore, can only extract limited amounts of cooling loads (Mathisen 1989; Cox 1990). Upward displacement ventilation shows a characteristic temperature profile caused by the convective currents due to the heat sources. As supply air is entering the room at floor level, the temperature gradient forms a barrier for low energy currents to reach high altitudes in the room. Due to comfort requirements, the temperature gradient between feet and head should not exceed 3 K, which further limits the cooling capacity of these ventilation systems.

In order to use this energy-efficient ventilation systems, another cooling source had to be found. The logical choice is a coupling of efficient ventilation systems with hydronic cooling systems, separating the tasks of ventilating and cooling the building.

# Cooling Power

The cooling power of hydronic cooling systems is limited by several parameters. First, the surface temperatures of the cooling elements should not be lower than the dew point of the air in the cooled zone. The dew point can be manipulated by reducing the air's humidity content. A more serious concern is the comfort effect of the asymmetrical distribution of the radiant temperature. Kollmar (Kollmar 1967) shows that for offices, ceiling temperatures of approximately 15°C are the lower limit.

The heat transfer between the room and the cold ceiling is based on radiation and convection. Whereas, the heat transfer of radiation is relatively easy to calculate, the convective heat transfer is a function of the air velocity at the ceiling level. This velocity is dependent on the room geometry, the location and power of the heat sources, and the location of the air intake and exhaust. Glueck (Glueck 1991) describes a model to calculate the cooling power of cold surfaces. Base temperature for the calculation is the operative temperature. Analog to the radiant floor heating system, Glueck finds an exponential function for the specific cooling power which is based on the temperature difference between the operative temperature and the surface temperature of the cooling element.

$$q_{tot} = 8.92\,(T_{air} - t_{ceiling})^{1.1}$$

with:

$q_{total}$ = specific cooling power [W/m$^2$]
$t_{air}$ = air temperature [°C]
$t_{ceiling}$ = ceiling surface temperature [°C]

assuming, that the operative temperature is approximately equal to the air temperature.

Results from the equation show high heat transfer coefficients which indicate significant air velocities at the cooling surface. Unfortunately, no attempt has been made to determine this velocity.

With a heat transfer coefficient of ($\alpha_{total}$ = 11...12 W/m$^2$K and a lower limit of the ceiling surface temperature $t_{ceiling}$ = 15°C one can reach a specific cooling power of approximately 110 to 120 W/m$^2$ through hydronic (radiative) cooling. In zones with more than one exterior wall, slightly higher specific cooling powers can be achieved due to higher radiative temperature differences. If forced convection is provided by the ventilation system, the cooling performance of the panel system can be increased.

## Energy Savings and Peak Power Requirements

Feustel (1991) states that the use of radiant cooling systems is an energy conserving and peak-power reducing alternative to conventional air-conditioning which is particularly suited to dry climates. The electrical cooling peak load, if defined as the load of the fans and the chillers, can be divided approximately into 37% for running the fans and 63% for using the chillers.

If ventilation and thermal conditioning of buildings are separated, the amount of air transported through buildings could be reduced by 80-90%. In this case the cooling would be provided through radiation using water as the transport medium. The ventilation has to be provided by outside air systems without the recirculating air fraction.

The elimination of return air also increases the efficiency of air-handling luminaires, as the convective heat extracted from the light fixtures is vented directly to the outside. Approximately 50% of the thermal cooling load due to lighting can be removed this way. Together with the reduced fan energy, an overall electrical cooling peak-load savings potential of about 40% seems reasonable.

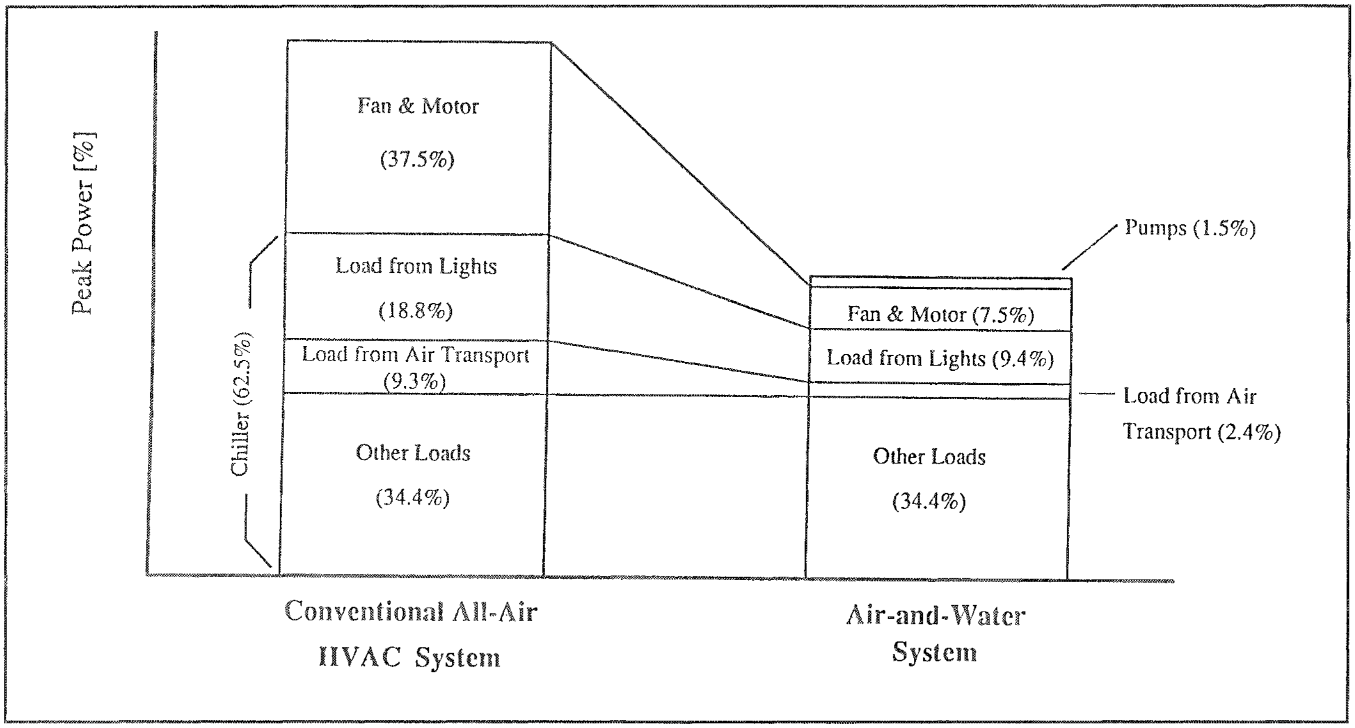

*Figure 2. Comparison of Electrical Peak Power Load for All-Air-Systems and Air-and-Water Systems (For the Air-and-Water-System, percentages are relative to overall peak power for the All-Air-System)*

## Example

In order to compare the electrical peak-power requirement for All-Air-Systems Air-and-Water Systems, the power requirement for a simple example has been calculated.

The example is based on an office with a floor area of 25 $m^2$, a two person occupancy and a total heat gain of 2000 W. The specific cooling load amounts to 80 $W/m^2$, which is in the range of radiant cooling systems. The room temperature is set to 26°C. Additional assumptions and design considerations used for this example are shown in Table 1.

The operation of an All-Air-System and an Air-and-Water-System can be seen in Figure 3 and 4.

The All-Air-System supplies the room as follows: The outside air is treated by a cooler which dehumidifies the air according to the required room condition. ASHRAE Standard 62 (ASHRAE 1989) requests a minimum air change rate of 36 $m^3/h$ Person. This means that for this example the minimum air change rate is 72 $m^3/h$. In order to remove the internal load, a recirculating air volume flow of 678 $m^3/h$ is required. The assumed outside air condition of 32°C leads to a mixing temperature of 25.6°C.

*Table 1. Assumptions Used for Comparison of Peak Power Requirements for All-Air-Systems and Air-and-Water-Systems*

| | Both Systems | |
|---|---|---|
| **Room Conditions:** | | |
| Cooling Load [$W/m^2$] | 80 | |
| Room Air Temperature [°C] | 26 | |
| Relative Humidity [%] | 50 | |
| Humidity Ratio [$g_{water}/kg_{dry\ air}$] | 10.6 | |
| Number of People [-] | 2 | |
| **Outside Air conditions:** | | |
| Air Temperature [°C] | 32 | |
| Relative Humidity [%] | 40 | |
| Humidity Ratio [$g_{water}/kg_{dry\ air}$] | 12.1 | |
| Enthalpy [kJ/kg] | 63.0 | |
| | All-Air-System | Air-and-Water-System |
| **Design Consideration:** | | |
| Outside Air Flow [$m^3/h$] | 72 | 72 |
| Supply Air Flow [$m^3/h$] | 750 | 72 |
| **Temperature Differences:** | | |
| Room Air - Supply Air [K] | 8 | 3 |
| Room Air - Ceiling [K] | 0 | 8 |
| Supply Water - Return Water [K] | -- | 2 |
| **Efficiencies:** | | |
| Fan: Hydraulic/Mechanical/ | 60/80/98 | 60/80/98 |
| Electrical [%] | -- | 60 |
| Water Pump [%] | | |
| **Pressure Drop:** | | |
| Supply Duct/Return Duct/Water | 500/250/-- | 500/250/40000 |
| Pipe [Pa] | 3 | 3 |
| COP [-] | | |

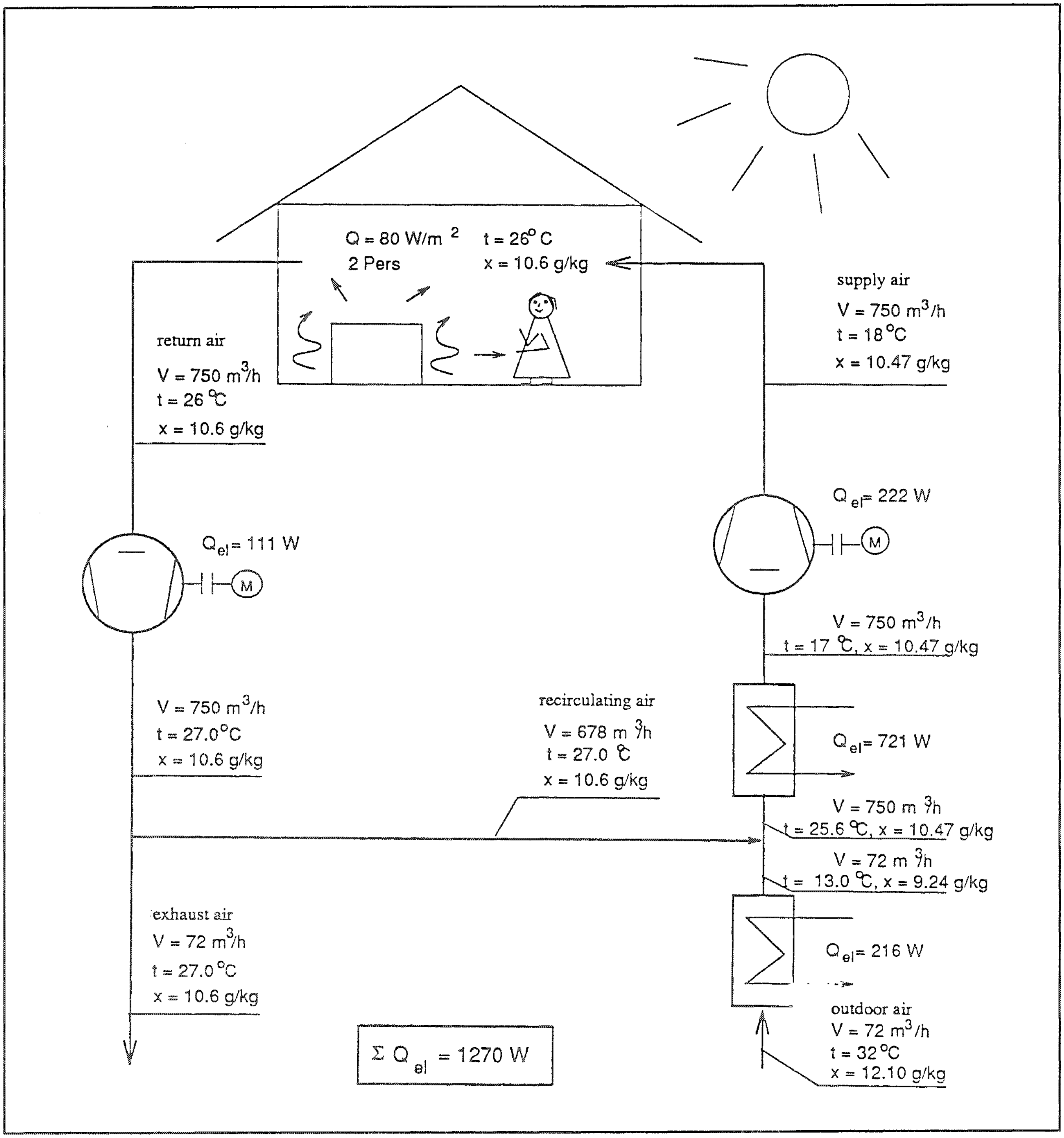

*Figure 3. Peak Power Requirement for All-Air-System*

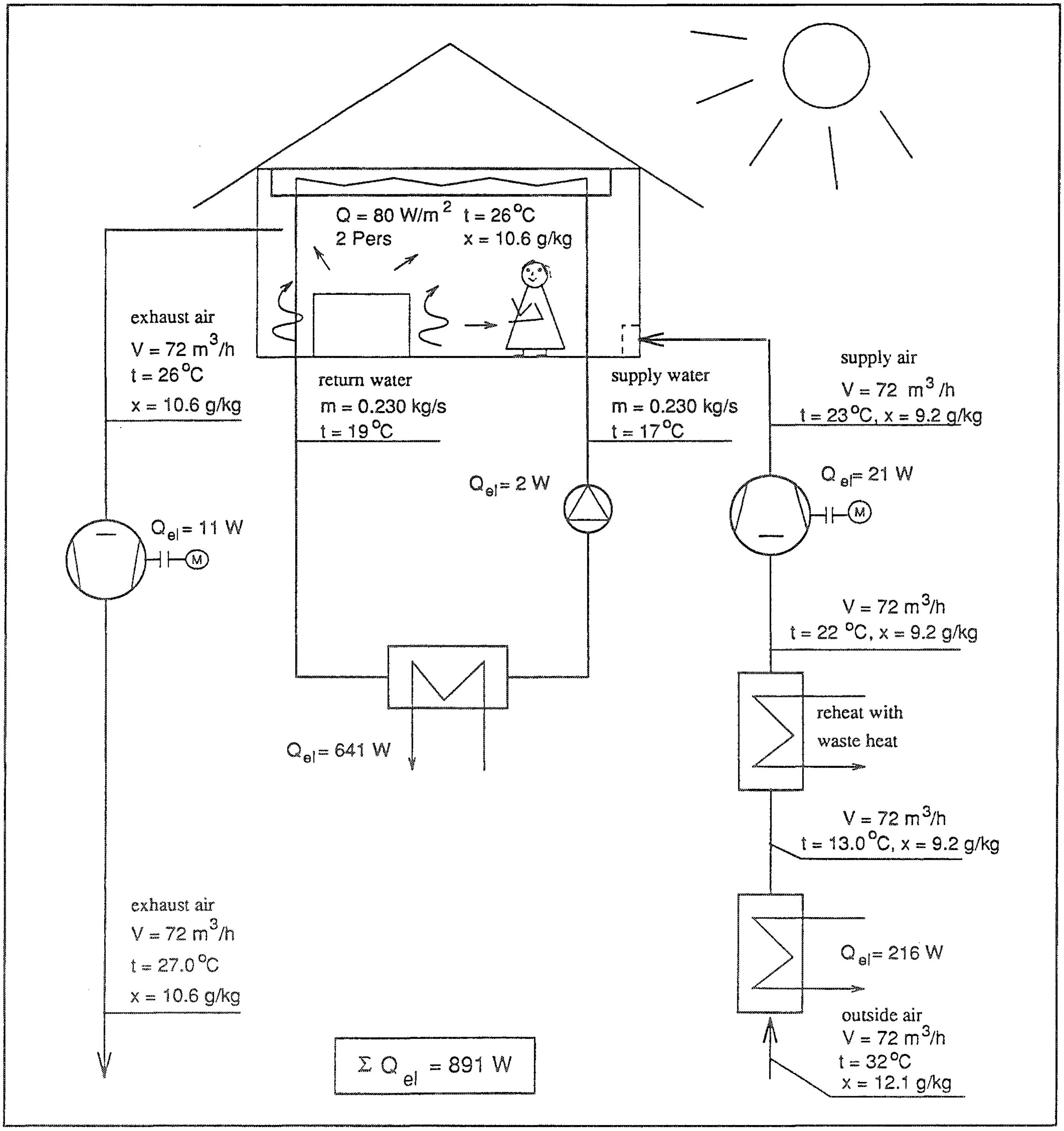

*Figure 4. Peak Power Requirement for Air-and-Water System*

After mixing, the air is treated by a cooling system. In order to adjust for the temperature increase due to the fan work, the air has to be cooled further down than the 18°C specified as supply air temperature. The temperature adjustment depends on the pressure drop, fan efficiency and volume flow. In our example the temperature raise has been assumed to be 1.0 K.

The electrical power for an All-Air-System amounts in this example to:

$$\Sigma Q_{el,All\text{-}Air\text{-}System} = 1270\ W$$

In order to be able to compare the two systems, the boundary conditions have to be the same. This includes the efficiencies of fans and motors, pressure losses for supply and exhaust ducts and chillers' COPs.

Whereas the All-Air-System removes the cooling load by means of supplying cold air, an Air-and-Water-System removes the load mainly by means of water. The air system's tasks thus are to supply the room with the necessary air exchange rate for hygienic reasons and to avoid humidity build up (control of the dew-point). In order to provide a stable displacement ventilation the supply air volume flow should be 3 K below room air temperature. Therefore the supply air temperature is reduced to 23°C, which allows a reduction of the cooling load by 2.88 W/m$^2$.

In order to control humidity, the outside air might have to be cooled below the supply air temperature. A reheater is installed which increases the air temperature using waste heat from the compressor. A more efficient way to use the supplied cooling energy would be to channel the air through building components and provide some of the conditioning with the air. The electrical power of the Air-and-Water-System amounts to:

$$\Sigma Q_{el,air+water} = 891\ W$$

Table 2 shows the electrical power calculated for an All-Air-System and an Air-and-Water-System.

If the total electrical power required by the All-Air-System is set to 100 %, the Air-and-Water-System has a power requirement of only about 70% (please note, that vented luminaires have not been utilized here).

*Table 2. Electrical Power Requirement to Remove Internal Loads*

| | All-Air System | Air-and-Water-System |
|---|---|---|
| Supply Fan | 222 W | 21 W |
| Air Cooler | 721 W | -- |
| Pre-Cooler/ Dehumidifier | 216 W | 216 W |
| Exhaust Fan | 111 W | 11 W |
| Water Pump | -- | 2 W |
| Water Cooler | -- | 641 W |
| Total | 1270 W<br>100% | 891 W<br>70.2% |

## Systems Available

Most of the hydronic cooling systems can be categorized into three system designs. The system used most often is the panel system. This system is based on aluminum panels with metal tubes connected to the rear of the panel. Building the panels in a sandwich design provides the necessary flow path between the panels, which increases the directly cooled panel surface and thus reduces the differences in the surface temperature.

Cooling registers made of small plastic tubes which are placed close to each other, can be imbedded in the plaster or mounted on ceiling panels (e.g. acoustic ceiling elements). This second system provides an even surface temperature distribution. Due to the flexibility of the plastic tubes, this system might be the best choice for retrofit applications.

A third system uses cooling registers embedded in a concrete ceiling. This component cooling system uses the thermal mass to phase-shift the cooling requirement of the room and the removal of the stored energy at times when the ambient conditions allow a more efficient heat removal. It is particularly suited to be operated solely in off-peak hours and is designed to be combined with alternative cooling strategies (e.g., night cooling) (Meierhans and Zimmermann 1992).

## Summary

Even though hydronic cooling has already been applied in the U.S., a breakthrough was never reached. In Europe, hydronic cooling was more or less abandoned after some applications in the late thirties and in the fifties. However, user complaints about All-Air Systems changed the designers' attitude towards these systems, which led to new system designs with better temperature control. Together with efficient ventilation systems and humidity control, the hydronic cooling system provides several advantages when compared to conventional HVAC-systems.

The reviewed literature shows that hydronic systems provide draft-free cooling, reduce space requirement, increase indoor air quality, reduce the energy consumption for heating and cooling, and are even cost effective if specific cooling loads are above 50 W/m$^2$ (Feil 1991). The peak load reduction due to fan power requirements is obvious.

## Acknowledgments

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## Endnotes

1. Displacement ventilation should not be mistaken for "plug flow" or "piston flow"; plume flow ventilation might be a better term.

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