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THE CHALLENGES OF AIR-CONDITIONING IN TROPICAL AND HUMID TROPICAL CLIMATES

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ABSTRACT

This paper firstly reviews the current practices in air- conditioning usage in tropical climates. Against the backdrop of escalating energy cost, the challenges faced by both manufacturers and users of air-conditioning are also highlighted. This is because of the fact that in some tropical countries almost one third of the electricity consumption is for air conditioning, which is needed virtually round the year at prevailing high ambient temperature. So reduction of electricity consumption for consumers is a pressing need and so is the deferment of capacity expansion for suppliers of power. As conventional systems are energy intensive there is a need for developing more energy efficient systems. In the same context, a number of promising hybrid systems e.g. evaporative cooling, desiccant cooling, hydronic radiant cooling and cooling strategies such as thermal storage air conditioning system have been reviewed using specific case studies.

Keywords: Conventional air-conditioning system, Hybrid air-conditioning system, Energy efficiency.

1. INTRODUCTION

Climates in the different parts of the world vary with season of the year and with geographical locations and hence, in very few places the natural environment is comfortable for human beings or suitable for a specific product or process throughout the year. There is, thus, a need for the control of the environment for human comfort as well as for some specific equipment, material or process. Heating is essential in cold climates while cooling is generally desirable in hot climates.

Figure 1 shows the climatic variation in different geographical zones of the world. Apart from temperature, human comfort is greatly affected by humidity. Consequently in addition to cooling, dehumidification and humidification processes are necessary for humid and arid tropics respectively. Indoor air tends to get foul due to absorption of pollutants from many different sources and the same needs to be controlled to an acceptable level. These processes involving artificial tempering of air and its proper distribution in an indoor environment, in fact, constitute air –conditioning.

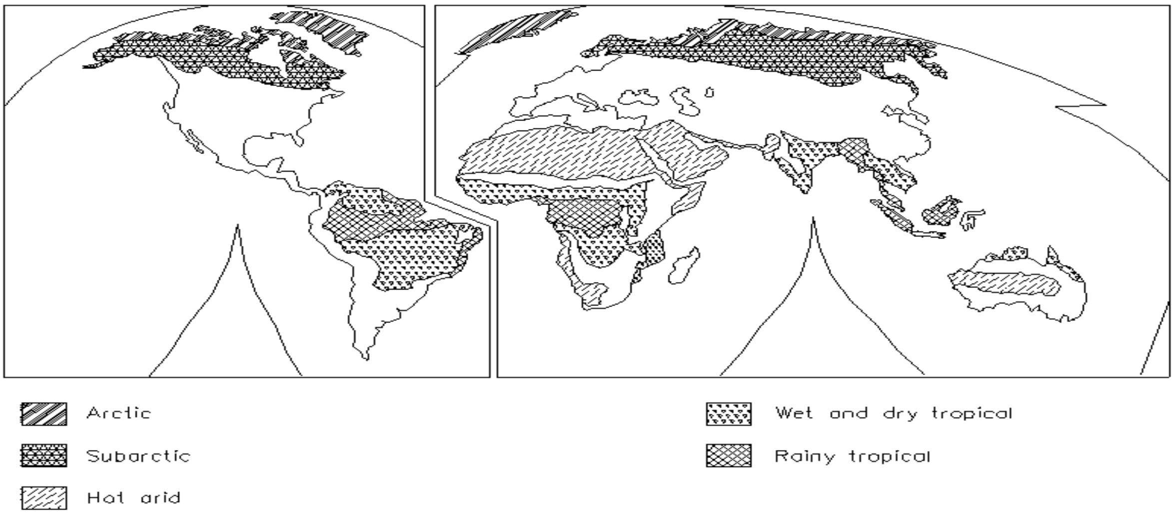

Fig 1. Different climatic zones of the world.

To provide these functions with most natural atmospheres, heating, cooling and regulation of thermal radiation will be required for temperature control; humidification and dehumidification will be required for humidity control and introduction of outside ventilation air, filtration, washing or odour absorption will be required for cleaning the air. By air conditioning, dust, bacteria, allergens such as pollens, noxious gases and odours can be removed from the air. It can assist in protection from such undesirable things as high levels of noise, and it can make possible the exclusion of harmful or annoying insects. Figure 2 illustrates the various functions of air conditioning. The use of air conditioning is no longer confined to the earth. Man has been able to stretch his reach to the outer space as well as to the depth of ocean with the help of air conditioning. Man's landing on moon, prolonged stay in orbital spaceships, space shuttles and submarines have all been possible because of man's ability to create artificial environment.

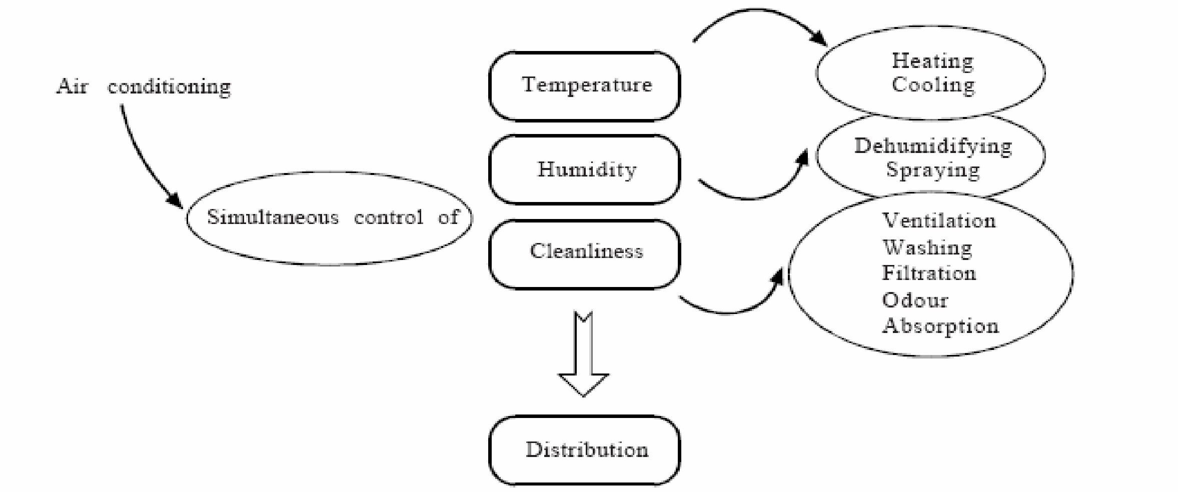

Fig 2. The functions of air conditioning

In some tropical countries almost one third of the electricity consumption is for air conditioning. This is because of the fact that air conditioning is needed virtually round the year and secondly load is higher because of higher ambient temperature. So reducing electricity charges for consumers is a pressing need and so is deferment of capacity expansion for suppliers of power.

2. CONVENTIONAL METHODS OF COOLING

In conventional central station air conditioning applications treated and cooled air is supplied into a room and then the same is brought back to the air conditioner. The same process is repeated. Figure 3 shows schematically a typical conventional central-station system.

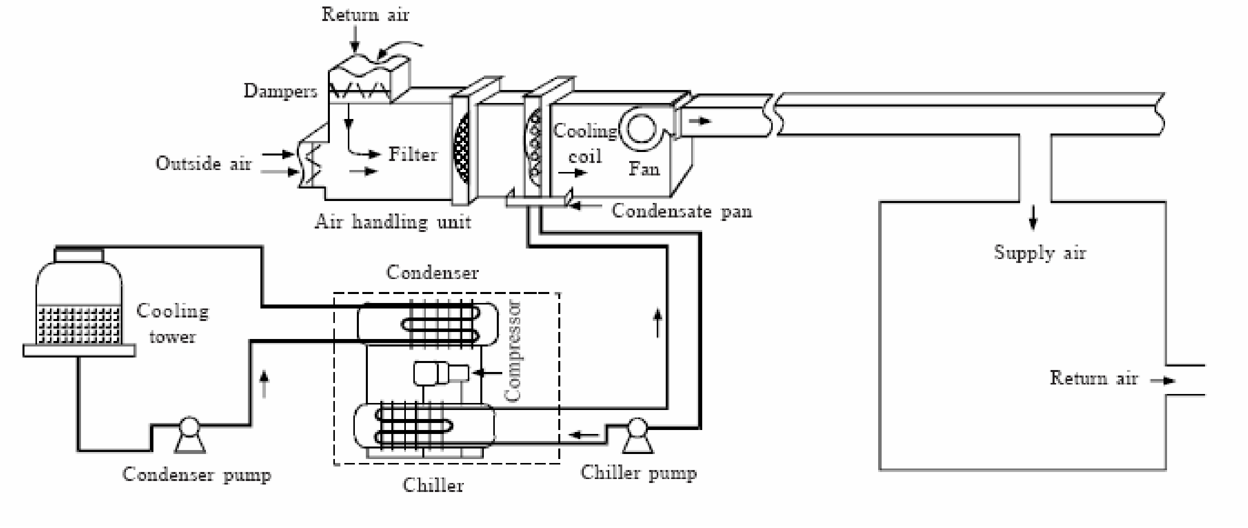

Fig 3. A typical conventional central-station system

Currently majority of the air conditioning systems uses vapour compression refrigeration cycles for providing the necessary cooling. Vapour absorption systems are also used where waste heat can be gainfully employed.

2.1 Vapour Compression Cycle- based Air-conditioning Systems

These systems are inherently energy-inefficient as the cooling coil has to carry out both cooling and dehumidification functions necessitating the cooling coil to operate below dew point temperature. Load variation in such systems is taken care of basically by two different strategies: (a) Constant air volume, variable temperature system (CAV) or (b) Variable air volume, constant temperature system (VAV).

Constant air volume (CAV) system

The systems are based on the principle of supplying a constant volume air into the conditioned space and the supply air temperature is varied in response to the space load. The main features of this type of system are that it is simple to design, install and operate, and has a high degree of flexibility. The ***terminal reheat type*** of CAV system allows zone or space control for areas of unequal loading, by incorporating terminal *reheat coils*, as shown in Figure 4.

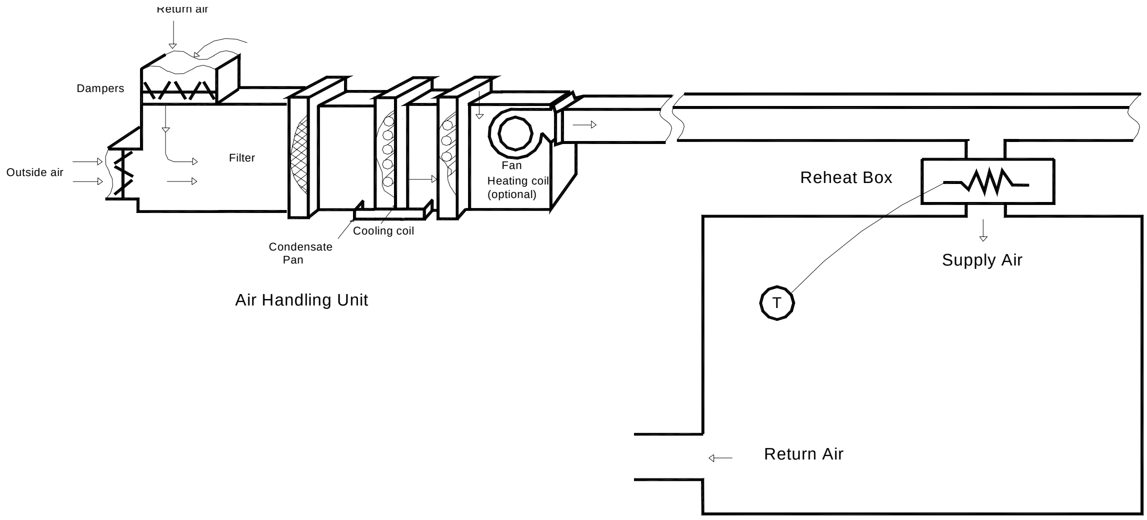

Fig 4. Schematic diagram of a CAV system with terminal reheat

Variable air volume (VAV) system

In a VAV system as shown in Figure 5, outside air and return air are mixed in an air-handling unit (AHU) and passed over a cooling coil to be dehumidified, cooled and delivered through a supply duct to the conditioned space. A terminal device is then employed for each zone which is controlled to vary the volume of cool air delivered to the space as dictated by the zone thermostat.

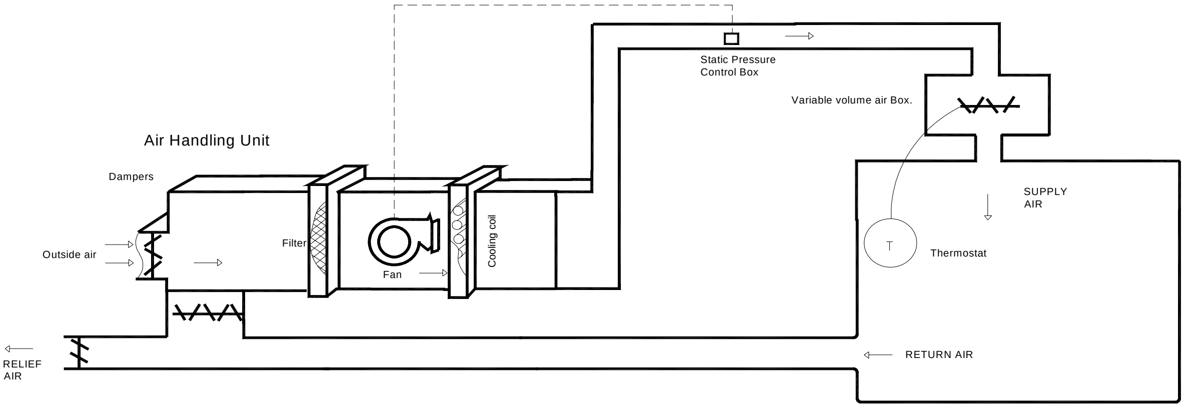

Fig 5. Schematic diagram of a Variable air volume system

The advantages generally attributed to the VAV systems are their versatility in individual zone controlled space, ability to do away with reheating and generally energy efficient performance. Plant and equipment can be down-sized where load diversity occurs. Since the volume of air is reduced with a reduction in load, the refrigerating plant and fan power follow closely the actual air conditioning load of the premises. Furthermore, it is claimed that the first cost of the VAV system is one of the lowest of any comparable quality system in the U.S.A. (Gupta et al. 1987). It has also been claimed that qualitatively VAV systems perform better in respect of temperature fluctuations (Sekhar and Chung, 1998). There are a number of disadvantages of such systems though, e.g. uneven temperature and air distribution causing lack of air motion, lack of fresh air at part load operation, complexity of design, poor air balance and energy saving not meeting expectations. However, there has been significant improvement of the VAV systems over the years resulting in marked improvements with regard to noise, pressure imbalance and control (Gupta et al. 1987, Gardner et al. 1988 and Geake et al. 1980).

Heating, ventilating and air-conditioning (HVAC) systems in many U.S. buildings have been converted to VAV systems and the performances of many such systems have been reported over the years. Johnson reported one system where the retrofit yielded an annual energy savings of 46.5% relative to constant volume operation (Johnson et al. 1984). Based on their simulation study, Ardehali and Smith (1996) reported a reduction in energy consumption by VAV systems in comparison with that of CAV reheat systems in excess of 50%. Sekhar et al. (1997) carried out energy simulation study for a number of types of buildings in Singapore using DOE-2 with a view to comparing the energy performances of VAV and CAV systems. He reported that the savings in total energy consumption of VAV system ranged between 11.5% and 25.7%.

Ameen et al. investigated the relative energy consumption of the two systems under simulated climatic conditions inside twin environmental chambers, where prototype air conditioning systems were installed and operated under identical simulated load conditions. They found that for office premises in tropical countries, where year-round diurnal temperature variation and load diversity is nominal, the advantages of VAV systems over CAV systems is at best marginal (Ameen & Mahmud, 2005). They highlighted the fact that unlike U.S.A., reheating is hardly practiced in commercial premises where load variation is relatively moderate during the office hours. Furthermore, VAV systems are generally 20% - 30% more expensive in terms of first cost in places like Singapore. The feedback from industry indicates scepticism in respect of the advantages of the VAV systems.

2.2 Vapour Absorption Cycle-based Air-conditioning Systems

These cycles are economical where inexpensive heat energy sources such as geothermal energy; solar heat and cheap natural gas are available in abundance. The simple vapour absorption refrigeration cycle is similar to the vapour compression cycle in many ways, however, it differs in the method employed for compressing the fluid. In this cycle the compressor is substituted by a generator, an absorber and a pump. There is another difference, that is, in addition to the *refrigerant* another fluid known as *absorbent* is used in vapour compression cycles. Two common combinations of refrigerant-absorbent are: (a) aqua-ammonia, where ammonia (NH_3) is the refrigerant and water or aqua is the absorbent (Figure 6) and (b) a solution of lithium bromide in water, water being refrigerant and lithium bromide (LiBr), which is a highly hygroscopic salt, being the absorbent (Figure 7). The former combination is suitable for low temperature application but is not used in air conditioning due to the toxicity of ammonia. The latter system is used in air-conditioning where waste heat or cheap fuel is available. Absorption cycles are not generally economical due to their low coefficient of performance (COP).

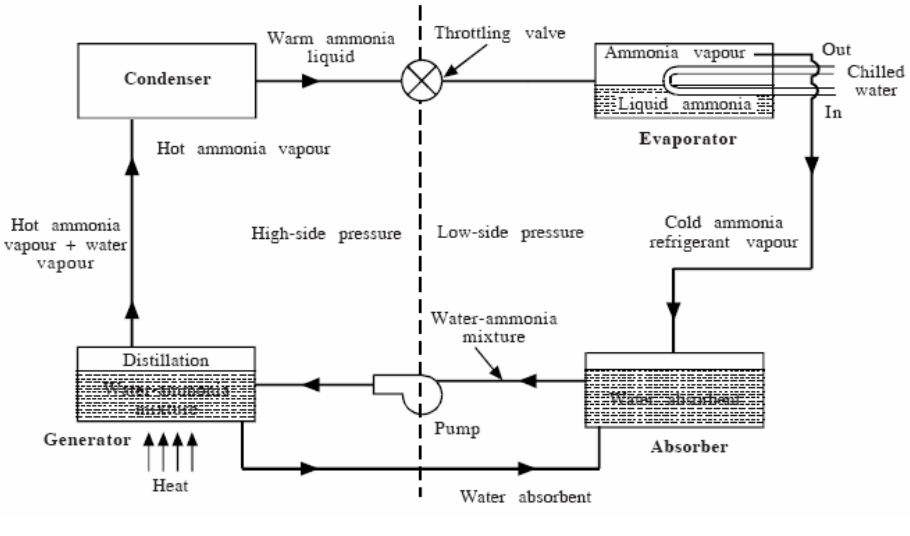

Fig 6. Schematic diagram of a aqua-ammonia vapour absorption cycle

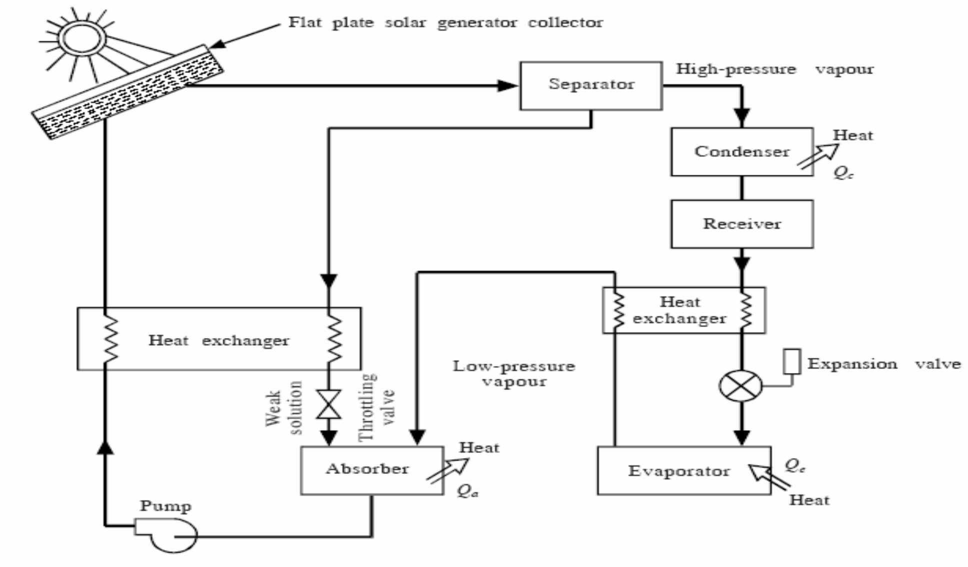

Fig 7. Solar -powered vapour absorption (LiBr H_2O) cycle used for air conditioning

2.3 Exotic Refrigeration Cycles used in Air-conditioning Systems

Apart from the conventional refrigeration cycles like vapour compression and absorption cycles, there are other methods of cooling that can be employed for specific applications. While conventional vapour compression cycle-based air conditioning is well established; use of other cycles is not so widespread. Air and gas expansion cycles are used in air conditioning of aircrafts. Thermoelectric refrigeration cycles are used in air conditioning of submarines for noise considerations. Similarly, vortex tube, another exotic cycle is used for providing air conditioning in mines. These cycles are limited to specific applications due to their very low efficiency, i.e. COP. However, they serve in systems having unique requirements.

3. OTHER METHODS OF COOLING

Aside from the traditional refrigeration systems, there are other methods of cooling including hybrid systems, which can be employed to create a comfortable environment. Evaporative cooling and desiccant cooling come under this category. Additionally, certain operating strategies like thermal storage air conditioning (TSARC) and district cooling are being used widely on economical considerations. In the backdrop of global concerns for indoor air quality, escalating energy costs and environmental concerns about the chlorofluorocarbon refrigerants, people are taking a new look at these systems and operating strategies. It is felt that an understanding of these systems and the operating strategies is essential to view the big picture related to cooling for comfort. In the same light these systems have been discussed hereunder.

3.1 Evaporative Cooling

Evaporative cooling is brought about by evaporating water (Figure 8) directly or indirectly in the air stream to bring down the dry bulb temperature of the air. The heat removed in lowering the dry-bulb temperature of the air is absorbed by the moisture, which evaporates and raises the humidity of the air. In some units capillary tubes or shredded wool, or metal wool is used instead of spray nozzles to present the necessary water surface for air contact.

Applications

Traditionally evaporative air cooling has been applied to industries to improve the comfort of workers in the hot environments of mills, foundries, power plants etc. They are also used in comfort cooling applications. In arid tropics evaporative cooling is being used widely and has proven very economical. However, the same is not practical in humid climates where ambient air is nearly saturated with moisture. In hot and dry climates evaporative cooling brings about reasonable degree of cooling at very moderate cost. It is also environmentally benign.

Cooling provided often could be insufficient; air circulation could create drafts and noise and filtering is not very satisfactory. The drawback of evaporative cooling in comfort cooling context is that air is humidified rather than dehumidified. Despite the same drawback, it is very popular in places like north India because it brings about relief in the form of lower dry bulb temperature at nominal cost. Furthermore, the capital cost of an evaporative cooling system can be a quarter of comparable capacity air conditioning unit while the operating cost could be less than a fifth. Evaporative cooling would be feasible only when the dry bulb temperature is very high (in excess of 35°C) with relatively low wet bulb temperature. The lowest temperature attainable by the water in an evaporative cooler is the prevailing wet bulb temperature of the air i.e. the temperature of adiabatic saturation. However, practically the lowest temperature achievable is about 4°C above the prevailing wet bulb temperature of the air. The commercial evaporative coolers sometimes referred to as “Desert coolers” approximates adiabatic saturation process.

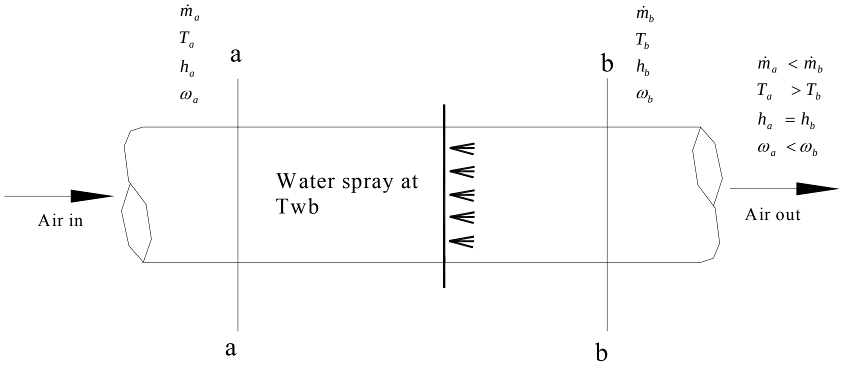

Fig 8. Evaporative cooling by an air washer

3.2 Hybrid Desiccant Cooling Cycles

Desiccant cooling is an environmentally friendly technology that can be used to condition the internal environment of buildings and which has seen renewed interest in recent years due to the growing awareness of global warming and other environmental problems. Unlike conventional air conditioning systems, which rely on high grade electrical energy to drive the cooling cycle, desiccant cooling is a heat driven cycle. They also allow a better indoor air quality. However, high first cost, unfamiliarity, long payback periods, maintenance uncertainties, and narrow marketing attempts have limited the acceptance of desiccant cooling systems (West et al. 1995).

Conventional vapour compression refrigeration cycle used in commercial air conditioners is energy intensive, while desiccant coolers are generally not economically viable as stand-alone systems. However, hybridization of these systems has the potential to be an economical proposition. In such applications, air conditioning can be carried out by dehumidifying the air by solid or liquid desiccant, followed by sensible cooling in two stages – first by water and then by an evaporator coil of a conventional vapour compression refrigeration cycle (Figure 10). The regeneration of the desiccant can be accomplished by condenser heat supplemented by a low-grade source of heat e.g. solar energy or industrial or commercial waste heat. Application of solar energy for air conditioning is inherently appealing, since available solar energy and the cooling load are in phase. Furthermore, regeneration of the desiccant is possible, even at temperatures between 60ºC and 100ºC, which can be supplied by an ordinary and relatively inexpensive flat plate solar collector.

System Simulation & Experimental Studies

Since Pennington's groundbreaking patent of desiccant cooling system in the fifties, over the years various aspects of desiccant cooling has been investigated to establish its effectiveness as an environmental friendly and economical alternative to the traditional systems based on vapour compression cycles. A number of simulation studies on desiccant cooling have been made and reported by various authors with respect to system parameters, climatic conditions and loads (Sheridan and Mitchel, 1985; Halliday et al (2002). Chau and Worek (1995) discussed the development of a simulation package to model open-cycle desiccant cooling systems operating in the recirculation mode. Dai et al (2001) presented an experimental investigation of a hybrid air conditioning system comprising sections of desiccant dehumidification, evaporative cooling and vapour compression air conditioning, having 20-30% higher cooling capacity than the vapour compression system alone. The feasibility of potential solid desiccant cycles for typical Indian conditions was analyzed and a novel cycle using regenerative evaporative cooling was proposed by Dhar et al (1995). Dhar and Singh (2001) reported the performance of four hybrid cycles for typical hot-dry and hot-humid weather conditions for the analysis of rotary dehumidifier based on the analogy method of Maclaine-Cross and Banks. Alizadeh and Saman[2002] conducted experiments on a prototype of the solar collector/generator where calcium chloride ($CaCl_2$) has been used as the absorbent solution. In another study Mazzei et al [2002] obtained the summer operating costs of a traditional air conditioning system and various desiccant cooling systems by using three software codes. For a retail store application with mean SHR ≈ 0.8, savings up to 35% was obtained for the desiccant system. Lowenstein & Novosel [1995] modelled a liquid desiccant system that cools and dehumidifies only the ventilation air of an office building in Atlanta, where the system is able to meet 52% of the building's seasonal cooling requirement. Techajunta et al [1999] presents an analytical study to evaluate the performance of a desiccant cooling system that uses silica gel as desiccant and electric light bulbs to simulate solar radiation. Based on their parametric studies, Henning et al [2001] claimed that combinations of sorptive dehumidification with a conventional, electrically driven backup system allow for primary energy savings up to 50% at low increased overall cost. Zhang et al (2003) presented one-dimensional coupled heat and mass transfer model, which has been validated using a real desiccant wheel.

Case Study - Solid Desiccant-based Hybrid Air Conditioner

A recirculation mode for an air conditioning system is considered, which comprises a dehumidifier, water-cooled heat exchanger, a vapour compression refrigeration unit, and a solar heating system. The schematic layout of the proposed system is shown in Figure 9. The solid desiccant dehumidifier is considered to be rotary wheels having three segments – one for adsorption of moisture, another for desorption of moisture, and the third one for cooling of the desiccant to remove the heat of condensation before it is used for adsorption. The regeneration of the desiccant is done by ambient air, which is to be heated by condenser heat followed by solar heating.

A psychrometric analysis has been carried out for a building in tropical city that requires a high ventilation rate. It has been assumed that 5000 L/s of air needs to be delivered to the premises of which at least 40% would be ventilation air. The inside conditions are 25ºC $T_{db}$and 18.5ºC T_{wb} and the outdoor design conditions are 34ºC and 28ºC. A sensible heat factor of 0.7 has been assumed. Dehumidification is considered as 0.0062 kg/kg of dry air. The air leaving the coil is assumed to be 90 per cent saturated. Corresponding temperature of the air leaving the coil is 13.5ºC and 12.5ºC. Cooling water is available at 31ºC for pre-cooling of dehumidified air to a temperature of 37ºC prior to cooling by the evaporator of the vapour compression refrigeration cycle. In this case, the cooling load is computed as 48.27 tons (169.79 kW) if the entire cooling is to be done by the vapour compression cycle. Using desiccant for adsorption of moisture followed by water-cooling prior to cooling by the evaporator, the capacity required is 38.31 tons (134.75 kW). Thus, a gross capacity reduction of 20.63% is indicated.

Considering a parasitic power requirement of about 3% for the pump, fan and desiccant wheel or additional pump in the case for liquid desiccant, still a system capacity reduction of about 17.63% is possible. Reduced system capacity not only lowers first cost but also result in lower operating cost. Based on life cycle cost analysis, the cost of additional items would be offset by savings in operating cost.

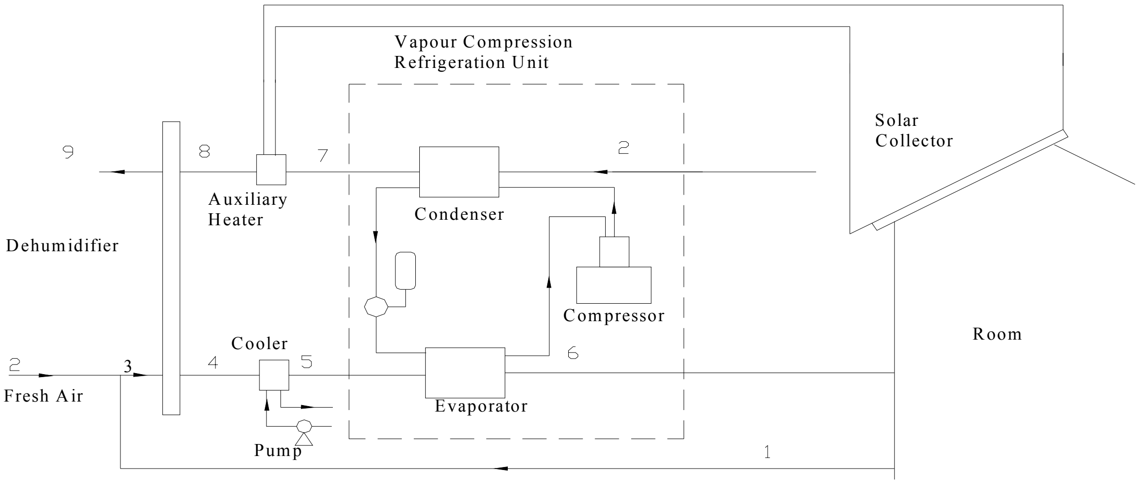

Fig 9. Schematic diagram of a heat pump assisted desiccant air conditioner

Considerable progress has been done in the field of desiccant cooling, which shows definite promise under certain climatic conditions; however, further improvement is necessary for it to replace conventional system. The use of a hybrid desiccant cooling air conditioner is feasible for humid tropical countries only for those applications where the ventilation air requirement is very high. Despite the inadmissibility of evaporative cooling in the humid tropics, downsizing of capacity of traditional vapour compression refrigeration unit for air conditioning is practical when used as a part of hybrid desiccant system.

3.3 Radiant Cooling Combined With Desiccant Dehumidification

A hybrid air conditioner comprising a chilled ceiling that would provide hydronic radiant cooling (HRC) and a desiccant dehumidifier (DD) providing dehumidification of air is a relatively new concept in the area of comfort cooling. This is combined with displacement ventilation (DV), where ventilation air is supplied at floor level and exhausted at near roof level. The predicted performance of the system indicated that chilled ceiling combined with desiccant cooling could save up to 40% of primary energy consumption, in comparison with a conventional constant volume all-air system (Zhang & Niu, 2003). In recent years both simulation studies and experimental research on HRC and displacement ventilation (DV) have been reported (Loveday et al. 2002, Alamdari et al. 1998 Rees et al. 2001, Mumma 2001, Novoselac et al. 2002). However, for the combination of HRC and desiccanrt dehumidification (DD), some simulation studies have been published (Niu et al.1995, Zhang et al. 2003). The inherent advantage of the system is that chilled ceiling temperature does not have to be lower than dew point temperature resulting in potential downsizing of the refrigeration system used. Another advantage claimed for radiant cooling is that cooling would be provided directly and more evenly to the occupants without causing draft (Feustel 1995). Although chilled ceilings have been used in European countries their acceptance in tropical climates is handicapped because of the fact that 100% cooling capacity cannot be met in tropical climates. It is, therefore, necessary to supplement the cooling capacity by another means. The supplementary cooling necessary may be provided by dehumidified and cooled ventilation air. However, there is a need to optimise the critical parameters of the hybrid system e.g. ceiling temperature, ventilation air temperatures (dry and wet bulb) and the supply volume flow rate in relation to the space cooling load and comfort criteria. Two critical issues are being investigated for the hybrid system, which are (a) energy saving potential and (b) if acceptable comfort parameters are achievable.

3.4 Case study

A case study highlighting the effectiveness of a desiccant dehumidifier combined with chilled ceiling is presented here. The case study is based on the specific system built at the Universiti Sains Malaysia (Ameen and Mahmud, 2005), where chilled ceiling combined with Desiccant dehumidifier has been constructed in a climate chamber of dimension 4.25m x 3.75m x 3m. They reported successful commissioning of the system without encountering condensation. They also reported that thermal comfort standards were achieved with chilled ceiling temperature of 15ºC.

The pre-commissioning study investigates the relative economy of the system vis-à-vis conventional air conditioners where cooling and dehumidification functions are carried out independently by chilled ceiling and solid desiccant wheel respectively. The inside conditions considered are 25ºC and 50% RH while the outdoor design conditions considered are 34ºC DB and 28ºC WB. A silica gel desiccant-based air dehumidifier is supplying variable quantity of dehumidified air to the climate chamber. An air-cooled chiller with nominal cooling capacity of 11.72 kW (3.3TR) has been installed to provide chilled water to the chilled ceiling panel and air cooler downstream of the desiccant dehumidifier. Flat panel type chilled ceiling occupying 70% of the total area has been installed. The ceiling temperature is maintained within a range of 15 -18°C by a thermostat controlling a 3-way by-pass valve in the chilled water line. Chilled water is tapped to cool air in the heat exchanger (Fan coil unit) downstream of the desiccant wheel. An additional evaporative cooler is interposed between this the desiccant wheel and the heat exchanger, to remove greater part of heat of condensation. The room cooling load is removed partially by the chilled ceiling and the balance by the desiccated and cooled ventilation air. Temperature and volume of the supply air and ceiling temperature are varied to ensure comfortable environment. The regeneration of the desiccant is done by ambient air heated by a built-in electric heater, to be substituted later by gas and solar heaters. The schematic layout of the proposed system is shown in Figure 10.

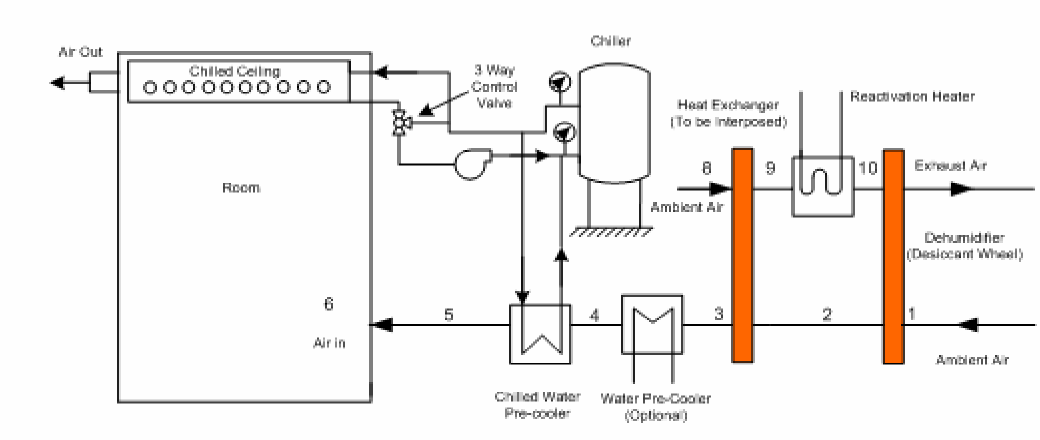

Fig 10. Schematic diagram of a HRC system combined with DD system

The case study is based on a space loading of 0.1 kW/m^2 and sensible heat ratio (SHR) of 0.7, which are representative of hot and humid climate. The simulation study has been carried out to determine the required supply air temperature for a range of CC temperature and supply air volume. The result has been graphically represented in Figure 11. This graph provides a guideline in respect of selecting the design parameters for HRC cum DV systems.

For the same room and space loading a conventional air conditioning system, as shown in Figure 1 is also considered. Considering 30 % ventilation air and a bypass factor of 0.15 for the conventional system with recirculation mode of air conditioning, the chiller load is 2.69 kW from the psychrometric analysis. This represents downsizing of the chiller by 22 %. The parasitic power consumption has not been analysed in greater depth at this stage. Considering net 7% parasitic power consumption after offsetting the fan power savings, the proposed system can achieve a reduction of refrigeration load by15%. A corresponding downsizing of equipment is also achievable.

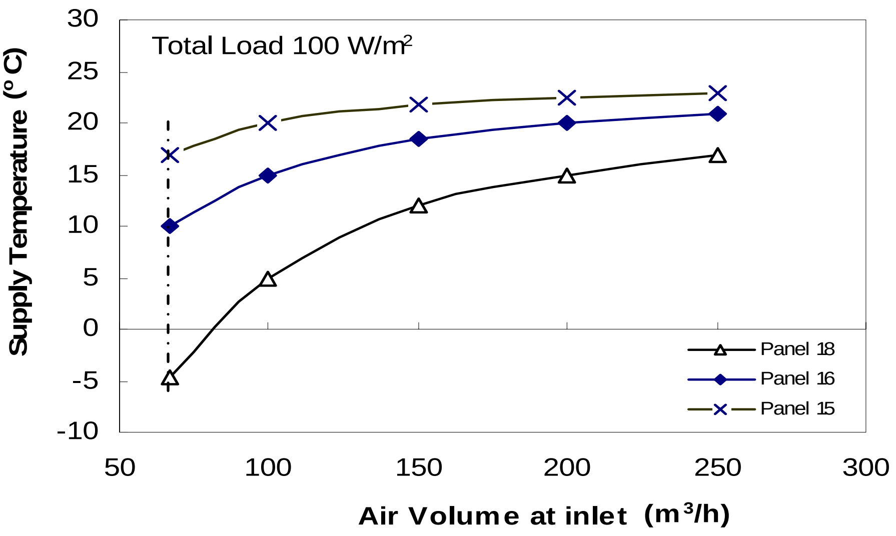

Fig 11. Required Displacement volume flow rate for different supply and panel Temperatures

Concluding Remarks

Considerable progress has been done in the field of desiccant cooling, which shows definite promise under certain climatic conditions. Generally the use of a hybrid desiccant cooling air conditioner is feasible for those applications where the ventilation air requirement is very high. Use of chilled ceiling combined with desiccant dehumidification is a very promising option with respect to energy savings as well as thermal comfort.

4. OTHER COOLING STRATEGIES

4.1 Thermal Storage Air Conditioning

Thermal energy storage for cooling or cool storage air conditioning has become well established in many countries e.g. USA, Japan and Taiwan as a useful load management technique. Cool storage utilizes an inexpensive storage medium with a high specific or latent heat, e.g. water, ice or eutectic salts to store cooling produced during off-peak hours for utilisation during peak hours. Conventional air conditioning chillers or industrial-grade ice making plants may provide refrigeration, which charge the storage tanks during off-peak hours. Circulating chilled liquid from storage through the building's air handling units, fan coils or a secondary heat exchanger provides on-peak cooling. By shifting electricity use to off-peak hours, both utilities and their customers are benefited. Cool storage helps utilities improve load factors, off-peak sales and enable them to defer the need for capacity expansion, whereas the commercial customers lower their electricity bills. Most utilities offer rate incentives to encourage customers to consider this alternative, which has substantially lower life cycle cost, particularly due to longer equipment and system life (Dorgan & Elleson, 1994). Figure 12 illustrates the principles of storage cooling system.

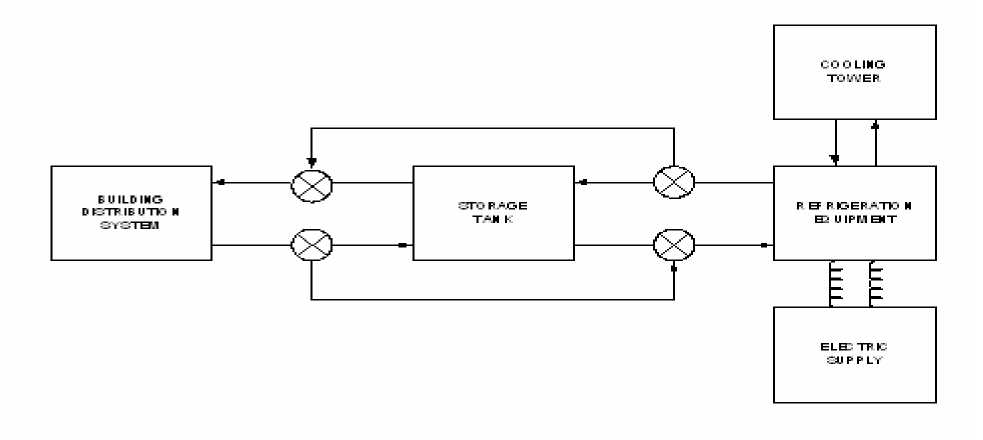

Fig 12. Principle of storage cooling system

Apart from the benefits of off-peak rates, cool storage helps to lower operating cost and improve efficiency of the chillers and compressors as they would be operating at full capacity in the night time when ambient temperature is much lower (McCracken, 1984). Consumers benefit by operating a smaller capacity compressor for long periods at or near its full capacity i.e. more efficiently than some non-storage systems having capacity utilization averaging only about 30%, which drives energy requirements. The savings generated from smaller compressors, pumps, and cooling towers offsets the extra first cost of the ice storage system. Cool storage is most cost-effective when a high, narrow cooling load profile occurs during the utility's on-peak hours (Figure 13). Moreover, demand peak charges are reduced significantly when the load profile is levelled. Typical high potential candidates for cool storage system are office buildings and retail outlets, while hotels or factory premises where air conditioning is needed round the clock are not suitable for cool storage as their cooling loads are distributed throughout the day and night (Gatley & Riticher, 1985). Figure 12 shows the principle of storage cooling system.

Two additional benefits of cool storage air conditioning are (a) combining chilled water storage and fire protection storage (Holness, 1993) and (b) in the case of ice storage opportunity to use cold air distribution system that result in a smaller air conditioning distribution system and fan coil units which make up the difference for the extra first cost (Dorgan & Elleson, 1989; Landry & Noble, 1991).

Operating Modes

There are two basic ways a thermal storage system can be sized and the charging and discharging of a thermal storage reservoir can be controlled. These are: (a) full storage (load shifting), and (b) partial storage (load levelling). The peak electric demand of a building is affected by the storage-operating mode. Figure 13 shows the cooling load profiles in conventional, partial storage and full storage systems.

Full Storage (Load Shifting) Systems

Under this operating mode, the refrigeration equipment charges the storage during the off peak hours. The cooling load is met from storage during the peak period. This operating mode requires a large chiller and a large storage tank. The chiller size varies between plus or minus 20% of the conventional chiller, depending on the length of the peak period. The advantages of full storage are simplicity in design, maximum reduction in energy bill and simple controls suitable for use with existing refrigeration equipment.

Partial Storage (Load Levelling) Systems

These are the more commonly installed thermal storage system. In a partial storage design, the compressor continues to run during on peak hours, but unloaded to some determined electric demand. On hot days, cooling is provided by both the storage and directly from the chiller/compressor. On moderate days, the storage may be able to satisfy the entire cooling load. Normally, partial storage systems are sized for 50%, but this figure can be varied to suit specific conditions.

Cooling Storage Media

Three different types of medium are used in cool storage systems: (a) chilled water, (b) ice storage, and c) phase change materials (PCM).

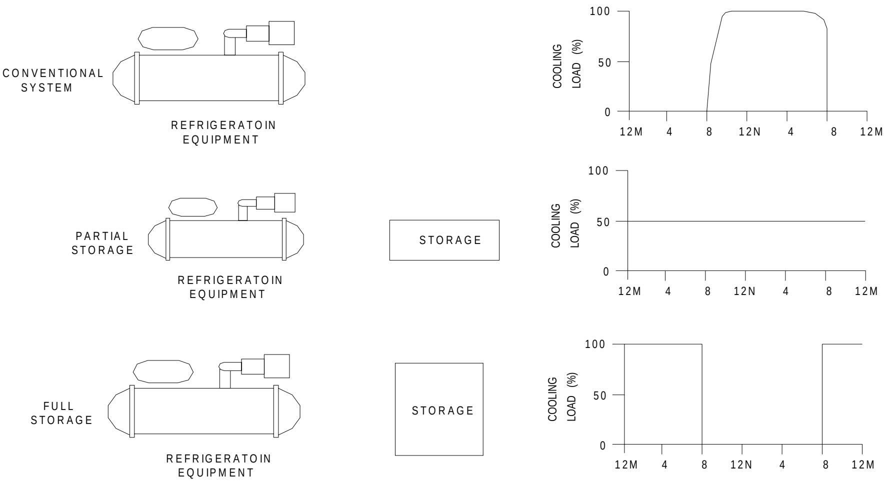

Fig 13. Cooling load profiles in conventional, partial storage and full storage systems (EPRI)

Chilled Water Storage system uses the sensible heat capacity of water to store cooling energy. In chilled water storage systems the storage water is typically chilled to 4.5 to 5.5°C and stores about 46.6 kJ/kg. Water storage systems can use the same reciprocating or centrifugal compressors that are used for conventional chillers, because the evaporator temperatures needed to chill the stored water are within the same design limits. Because of overall simplicity in design, control installation and maintenance, naturally stratified chilled water system used to be one of the most commonly used system in the US in the early 80's (ASHRAE, 1984).

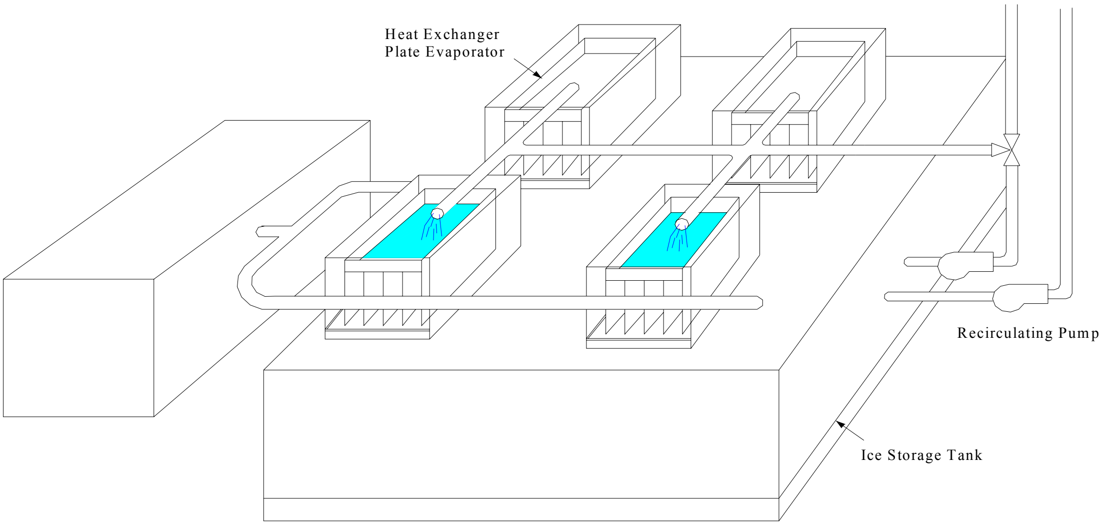

Fig 14. Schematic layout of an Ice Harvester

Ice Storage Systems use the latent heat of fusion to store the required cooling energy. Since ice can store more energy than water in the same amount of volume, therefore, ice storage system utilises lesser space (one fourth to one sixth) to store the required cooling energy as compared to chilled water system. There are two types of ice storage systems:

(a) **Static or ice-on-coil** systems, where ice builds on the heat transfer surface (coils), and
(b) **Dynamic** or **ice harvesting** systems, where ice is periodically removed from the heat transfer surface by injecting some hot refrigerant gas or mechanical scraping. The ice is usually deposited into storage reservoirs in crushed or chunk form. Water is then circulated through the reservoirs as needed to meet the building cooling loads. These ice builders (Figure 14) are available in modular sizes for indoor or outdoor installation.

Phase Change Materials Systems are similar to ice storage systems in that they utilize the latent heat of fusion of a solid to store more cooling energy in a given space and, hence, require less space than chilled water systems of same capacity. The most common phase change medium used is eutectic salt solutions, which freeze at around 8°C, a temperature level that does away with the need of low evaporator temperature required by ice systems

Current Status

On the Asian scene, Japan and Taiwan, Hong Kong have taken the lead in the usage of thermal storage in air conditioning due mainly to their dependence on the imported energy and relatively developed economy. It is interesting to note that Hong Kong has a tariff arte specially meant for ice storage system. There is no charge for demand up to the level of the demand during 0700 to 2300 hours.

In Singapore the rebate for electricity tariff for off-peak hours are merely 10.6% as against 0% in Thailand 74.6 % in Japan and 55.2% in Taiwan. Furthermore, demand charge in Japan and Taiwan are 174.7 % and 28% higher respectively than that of Singapore. So obviously, while there is huge incentive in switching to cool storage air conditioning in Japan and Taiwan, justifiably, to date no thermal storage system is in use in Singapore. If the rates are compared between two neighbouring countries of Malaysia and Singapore, it is observed that rebates in Malaysia 297.2% higher than in Singapore and the demand charge is 56.25% higher. In Thailand the matter is even worse, and the issue is virtually dead

4.2 Case Study

A study was carried out for a six-storey office building in Singapore; where there is need for year-round air conditioning, to ascertain the feasibility of cool storage air conditioning vis a vis conventional system. Ice storage system was considered for 50%, 60%, 70%, 80% and 100% storage. The lowest pay back period was 14.8 years for 60% storage while that for 100% was 22 years. Obviously with the prevailing tariff structure, switching to cool storage air conditioning was not a judicious choice. Applying the tariff rates and demand charges prevailing in Taiwan, however, the pay back period reduces to mere 5 years. The study points out the fact that with user-friendlier tariff incentive makes the additional investment viable. Figure 14 shows how payback period varies with percentage discount between peak and off-peak rates for various demand charges for a typical storage (50%). Figure 15 shows how with existing tariff rates varying demand charges affect the payback periods.

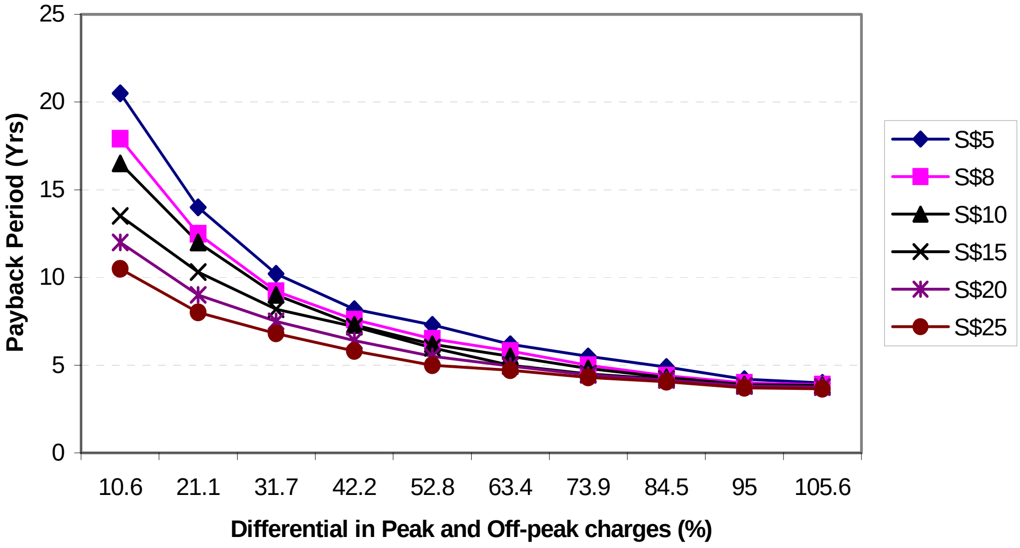

Fig 15. Graph of payback period vs. percentage discount between peak and off-peak rates for various demand charges (50% storage)

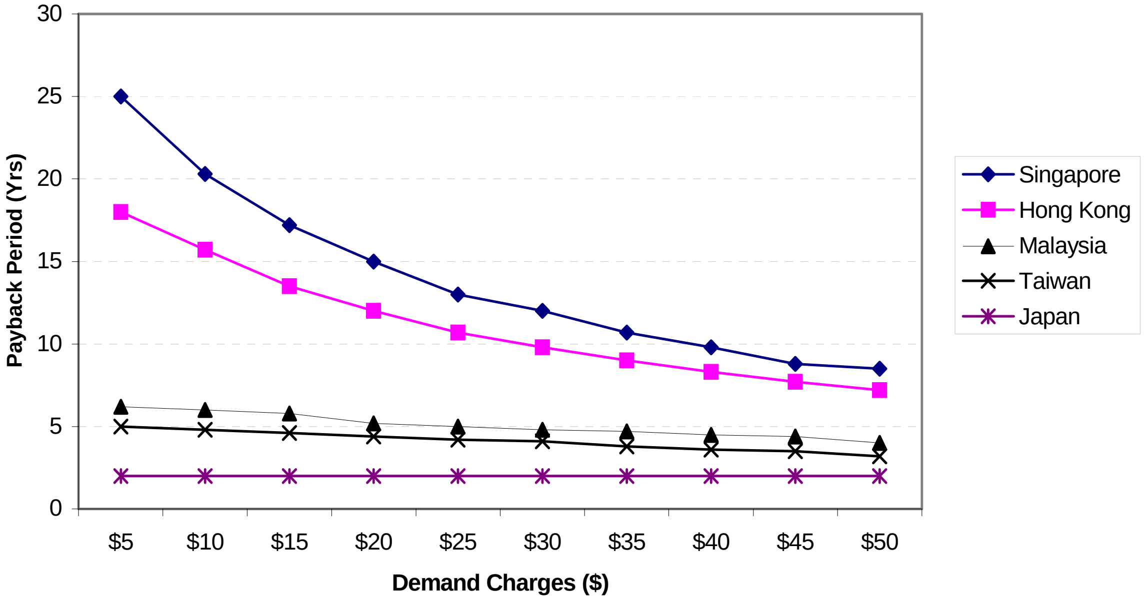

Fig 16. Graph of payback period vs. demand charges for various Asian countries (100% storage)

Concluding Remarks

Switching to cool storage air conditioning is a win-win option for both consumers and suppliers of electricity as the consumers benefit from reduced electricity charges and the suppliers of power benefit due to deferment of capacity expansion. However, large-scale thermal storage air conditioning would only be viable when substantial rebate for electricity usage during off-peak hours is available and higher demand charges are levied. The methodology as to how to decide on the peak and off peak differential and the optimum threshold of demand charges for a targeted payback period has been demonstrated. Referring to similar graphs as Figure 15, appropriate tariff differential and/or demand charges can be chosen based on the level of payback period targeted. Likewise graph similar to Figure 16 can be referred to for arriving at decision for revising demand charges without changing current tariff structure. Based on the prevailing electrical tariff rates and demand charges in a number of Asian countries, an analysis has been carried out to highlight why certain countries have better incentives to switch to storage-based air conditioning.

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