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Optimization of ambient energy component in large mixed mode central AC plants

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This paper presents the study of energy efficiency improvements of central air conditioners (AC) through the optimal integration of natural air ventilation functions. There is potential for energy saving through the shifting to mixed mode air conditioning invoking the ambient energy for cooling. An optimization study shows that up to an ambient temperature of 22 ˚C, passive cooling can be used and beyond that temperature active cooling is required. Simulation of energy consumption for air condition has been undertaken in 5 major cities of India, viz., Bengaluru, New Delhi, Mumbai, Kolkata and Chennai. The energy efficiency specified as per ECBC (energy conservation building code of India) is 80-90 kWh/m²/year for AC and can only be reduced through passive cooling components. Results indicate that it is possible to reduce the energy consumption by almost 50 % through the use of natural air ventilation cooling.

Keywords: *Air conditioning, mixed mode AC, ventilation air cooling, passive systems, evaporative systems, energy efficiency*

1.0 INTRODUCTION

Central air conditioning (AC) systems can be classified as:

- **Active systems** (vapor compression cycle)
- **Passive cooling systems** (natural ventilation through windows, chimneys, etc.)
- **Mixed mode systems** (combination of active and passive systems)

Active AC systems are energy intensive whereas passive systems have low energy intensity. However, passive systems are limited in their capability to deliver cooling effect under all operating conditions of temperature and relative humidity over the whole year.

Passive cooling can be achieved in a variety of ways:

- Ventilation through window opening-can be driven by wind on one single side or to cross ventilation.
- Stack ventilation through ventilation boxes connected to multi-storey chimneys, roof vents, structural fins, under-floor ducts, etc.
- Using the room as a chimney by drawing in fresh air at a low level and exhausting it at the top.
- Atria for variant of stack ventilation, where the multi-storey volume created for circulation and cross ventilation across rooms.
- Evaporative cooling

Passive cooling or natural ventilation has the advantages of:

- A sustainable cooling solution.

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- Good fresh air supply.
- Low energy and maintenance costs.
- Free night time cooling.
- More usable floor area due to less lower sized or no active AC system.

The zero energy building concepts are showing trends of turning into a design reality. Thermal simulation models are meeting the design requirements of achieving zero net energy in buildings [1,2]. Evolutionary algorithms have been used in solving constrained building design problems for achieving near zero energy buildings [3]. The role of ambient energy in the comfort AC design of buildings has increased in the level of reliability to provide bankable solutions for year round performance [4-6].

On the other hand active systems have the advantages of:

- Ideal control over indoor air temperature under all weather conditions.
- Possibility of ice energy storage systems for peak power storage management.
- Optimal energy efficiency at low loads through variable frequency drives (VDFs).
- Energy savings options with cold recover wheels and heat recovery system.

In mixed mode air conditioning systems (MM-AC), natural ventilation is used as the primary means of providing cooling, which is then topped up by active vapor compression cooling. MM-AC are generally classified based on the technique of natural and the operational mode as:

- **Contingency mode**: Here both the systems are independently installed- active and passive separately and switched over by the end user. They are not mutually exclusive.
- **Zoned mode**: Here a certain zone of the building is fitted with active system and another zone is based on passive systems.
- **Complementary mode**: Here both systems are provided in the same zone. Operation is either mutually exclusive or simultaneous. There are three modes of complimentary operation:
    - Alternating operation
    - Changeover operation
    - Concurrent operation

MM-AC strategy brings together the benefits of both active and passive systems to provide:

- Low energy intensity.
- Low operating costs.
- Accurate conditioned air control.
- Improved comfort through inclusion of inherent air change.
- Better tunability of the capacity to match the load.

MM-AC have the inherent advantage of balanced cost, balanced energy consumption and balanced energy efficiency as compared to the active systems. MM-AC designs are limited in present usage because their design principles are not well exploited in all cases. However, a good level of success has been achieved towards the development of MM-AC plants [7-9]. MM-AC hybrid variations have been adopted for reducing the electrical energy requirements of building AC [10,11]. Low energy buildings based on MM-AC have been design to meet the standards of comfort [12-15]. A review of technologies and strategy to improve energy efficiency of MM-AC plants indicates that fuzzy, predictive and adaptive controls are successful [16-19]. A primitive parts model (considering the basic heat and mass transfer) has been successfully used to match and map complex building topologies [20].

Evaporative cooling [21] and hybrid storage [22] have also been integrated into MM-AC systems for achieving better comfort conditions.

Ventilation has played a major role in the effective implementation of MM-AC [23-25]. Under floor and overhead air distribution; displacement ventilation and chilled ceiling have been used for MM-AC of commercial buildings [26-30]. Monitoring, controls and fault diagnostics of ventilation are vital for effective implementation of MM-AC systems [31-36]. Controls for MM-AC include expert systems, energy flow controls, logic based controls, fuzzy logic based controls and capacity controls based on economics [37-41]. Temperature zoning also plays a role in improving energy efficiencies of MM-AC systems [43].

With the use of MM-AC aided by design support, controls and temperature zoning, the projected saving in energy or the energy efficiency based on paid electrical energy can be reduced by 40 to 50 % without sacrificing comfort. This paper discusses the design aspects of MM-AC plants for large scale AC plants for conditioning of Malls, working spaces in IT halls, sitting areas in large office complexes, etc., where the use of ambient energy via ventilation fans can bring about increased energy efficiency.

2.0 INDICES OF ENERGY EFFICIENCY

Energy efficiency in air conditioners (AC) (of which compressors are the primary energy consuming components) is basically achieved by closed loop communication and tracking of the load. Energy conservation does not imply compromise of the demand load. The load could however be optimized by tuning the temperature and humidity, but essentially the load has to be met and the demand fulfilled. Three important interrelated indices of energy efficiency [1] are:

SP (Specific electric power) (kW of electric power input per tonne of refrigeration =kW/TR) [1 TR=3. 516 kW]

EER (energy efficiency ratio) = cooling load (kW) /electric input (kW) which is expressed on the basis of p.u., it is generally in the range of 2.3 to 3.1.

COP (coefficient of performance) is given by the ratio 3.516/SP

SEC (specific energy consumption) is the annual electrical energy consumption per unit space kWh/m^2/year.

TABLE 1

SPECIFIC POWER FOR A COMPLETE CENTRAL AC PLANT OF 500 TR

Sl. No	**Particular**	**No. of units in operation**	**Power input per motor (kW)**	**total power input (kW)**	**Specific power (kW/TR)**
1	Compressors	1	447	447	0.89
2	Chiller pumps	1	55	55	0.11
3	Condenser pumps	1	55	55	0.11
4	Cooling tower fans	1	18	18	0.04
5	AHR fan motors	26	13.3	345.8	0.69
	Total			920.8	1.84

Table 1 gives the breakup of the specific power of major power consuming equipment in 500 TR central AC plant [1].

The internationally accepted annual performance index is the SEC. As per the Energy Conservation Building Code of India (ECBC) [45], the electrical energy consumption of buildings must be within 120 kWh/m^2/year for AC buildings and 25-40 kWh/m^2/year for non AC buildings. The AC contribution can be taken as 80-90 kWh/m^2/year.

The on time to total time ratio is a ratio of the period under which the AC plant is in operation and drawing full, active power of the total time period under consideration (24 hours/day; 720 hours/month or 8760 hours/year). This is a temperature dependent factor and is designed to be around 0.3 for the of ambient temperature of 33-34 ºC. As the temperature shoots up this ratio also increases. Theoretically this ratio should be zero when the ambient temperature matches with the comfort temperature of 23ºC but invariably the building inside temperature will be several degrees higher than the outside ambient temperature because of greenhouse and heat trap necessitating the operation of AC plants.

3.0 MODIFICATIONS TO CENTRAL AC PLANT FOR CONVERSION INTO MM-AC

The central AC system was traditionally based on the constant chilled water flow system through regulated flow systems and chilled air flow systems are also in vogue. The variation in AC cooling effect individual air handling units (AHUs) was through three way valves on the chilled water line at the entrance to the AHUs. These are motor operated valves based on thermostatic temperature control of the chilled air-line. This traditional method of control suffered from problems such as:

- Low temperature differential across the chiller.
- Poor control due to choking of bypass line of chilled water valve.
- Poor turn down of the central AC plant.
- Over cooling in the AHU room short circuiting of chilled air from the conditioned space to the AHU return line without cooling the space.
- Uncontrolled operation of AHU on the air side.

Earlier designs of constant chiller water flows have given way to variable and independent (decoupled) flows in the primary (chiller) and secondary (AHU) circuits through variable frequency drives (VFDs). In addition, three way motor controlled valves are in use in the AHU coil circuit.

Traditionally the capacity control (up to 40 % of the design capacity) of the chillers (source side) was through cylinder unloading which was a very energy inefficient practice with very little reduction in energy consumption of the chiller compressor motors. With the advent of VDFs, a turn down to 12.5 % of the maximum continuous rating (MCR) is possible to be achieved. While the chiller capacity is turned down, thought must be given for matching or corresponding capacity control on chiller water conveying systems side also.

Figure 1 gives a view of the basic configuration of a chilled water circuit. The pass high pressure (HP) to low pressure (LP) bypass helps in flow balancing.

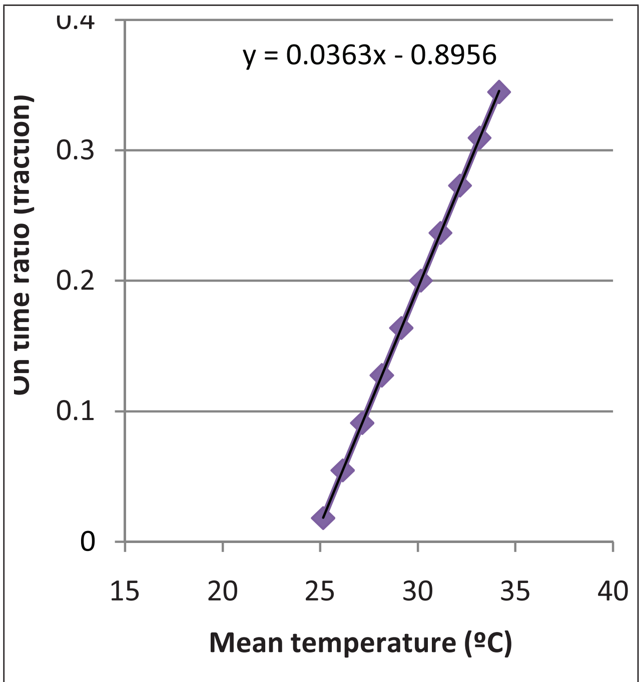

FIG. 1 VARIATION OF ON-TIME TO TOTAL TIME RATIO FOR VARIOUS AMBIENT TEMPERATURES (ºC)

Figure 2 shows a view of the circuits in the AHU. The process of natural air intake through windows, stakes and chimneys have the problem of providing inadequate ventilation (due to low kinetic energy and

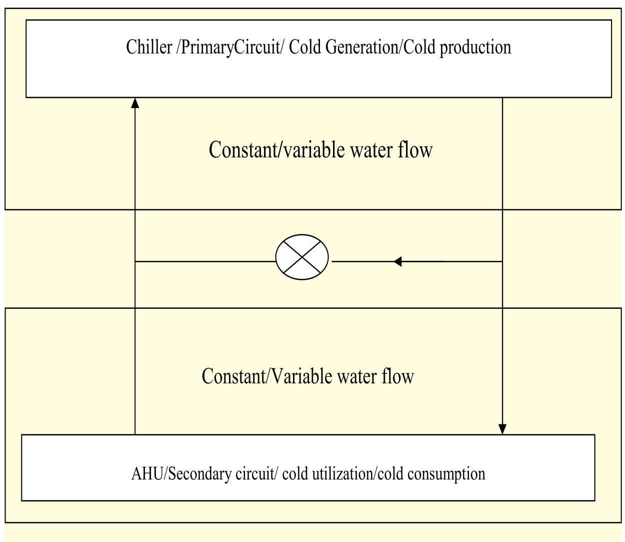

FIG. 2 BASIC CONFIGURATION OF THE CHILLED WATER CIRCUIT.

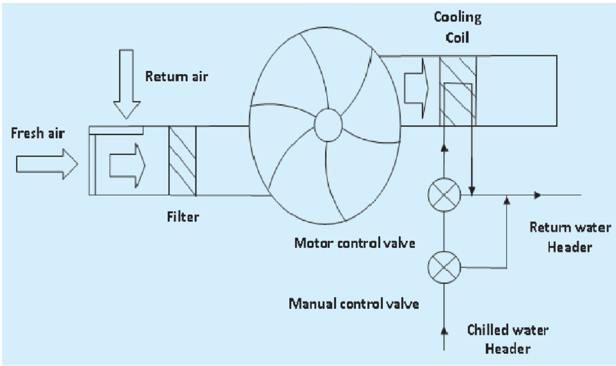

FIG. 3 BASIC CONFIGURATION OF AN AIR HANDLING UNIT WITH A THREE WAY WATER BYPASS VALVES

directivity) on retrofitting into large existing building spaces besides the problem of carry over of dust. Hence for the present optimization process the ventilation air fans are used for providing fresh air with the following configurations:

- Sensible cooling -without chilled water cooling
- Cooling with partial (top-up) chilled water circulation through the AHU.
- Cooling through evaporative cooling in ventilation duct.

4.0 RESULTS OF THE PERFORMANCE OF MM-AC PLANTS VIS-À-VIS CONVENTIONAL AC.

The results pertain to office space with traditional window and door sealing. The data on energy indices of AC and MM-AC systems are based on experimental data of motor power and cooling load actually measured in AC plants of over 500 TR and fitted to a curve of the type,

$$Y=A_0+A_1X \quad \dots (1)$$

Where A_0, A_1 are the coefficients in the curve fits, X is the dependent parameter and Y is the independent parameter.

Table 2 gives the curve fits for the SP and on time to total time ratio for the cooling loads based on the experimental data.

The experimental data on ventilation flow per TR (m^3/s per TR) (m) is dependent on the temperature differential between ambient and conditioned air (ΔT) as,

$$m=-0.3238 + (0.8126 (\Delta T) -0.2128 (\Delta T)^2 + 0.0175 (\Delta T)^3 \quad [R^2=0.97] \quad ....(2)$$

The experimental data for SP (kW/TR) for ventilation as a function of (ΔT) is given by,

$$SP= -0.5084 + 1.2759(\Delta T) -0.3342 (\Delta T)^2 + 0.0274 (\Delta T)^3 \quad [R^2=0.98] \quad ....(3)$$

Using the curve fitted experimental data, the simulation results are presented for the following cities in India:

- Bengaluru
- New Delhi
- Mumbai
- Kolkata
- Chennai

The day (24 hr) is divided into three shifts (time slots) as:

- 09:00 - 16:00
- 17:00 - 24:00
- 01:00 - 08:00

The cooling loads are worked out for these three time slots. These time slots are formed on the basis of user requirements. The major user requirement is during the 1st time slot where the commercial activities take place. The second time slot is normally for software centres, shopping malls, etc. The third time slot is for round the clock offices, warehouses, etc., MM-AC is used for the first time slot where the maximum cooling load is required.

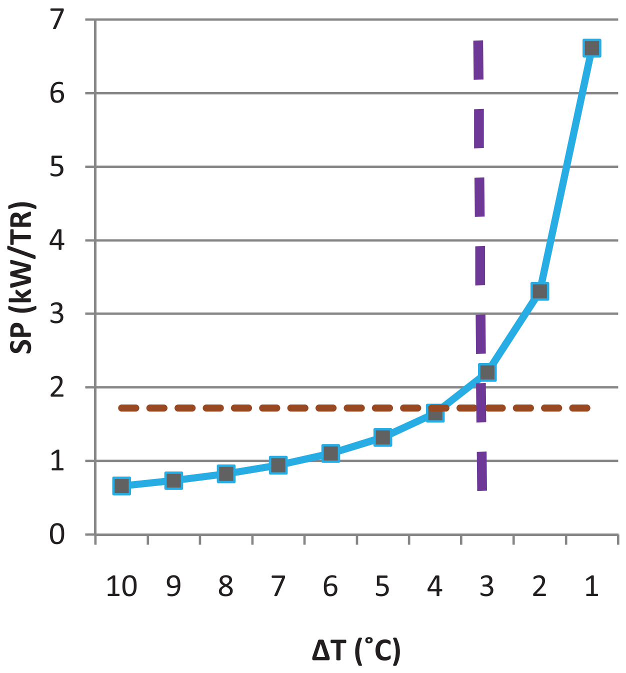

FIG. 4 OPTIMIZATION OF MIXED MODE AC PLANTS –VARIATION OF SP IN VENTILATION MODE WITH SP IN NORMAL MODE (HORIZONTAL DOTTED LINE AT 1.72 KW/TR) CROSS OVER AT 3.84°C.

Figure 4 gives the optimization of the mixed mode of AC with temperature differential below 24°C. It is seen that for ambient temperature up to around 22°C or conditioned space temperature minus 4°C, the passive systems are lower in energy intensity. If the temperature is above 22°C, then active systems would be more economical.

Figure 5 gives the on time to total time ratio for various average ambient temperatures.

The range of ambient temperature for the major cities is given in Figure 5. The annual cooling effect is given in Figure 6 for the major cities.

Table 3 gives the annual energy consumption for conventional and MM-AC plants for year round performance.

TABLE 2

CONSTANTS IN THE CURVE FIT FOR ENERGY EFFICIENCY FACTORS OF AC PLANTS OF 500-1000 TR.

Sl. No.	Particulars	A_0	A_1
1	X = Ambient temperature (21 to 50°C) Y = No load (no occupancy load) cooling load of air conditioner (0 - 0.20) kW/m^2 R^2= 098	-0.1694	+0.0074
2	X = Ambient temperature (21 to 50°C) Y = Total cooling load of air conditioner (0 - 0.35) kW/m^2 R^2= 0.99	-0.3049	+0.00125
3	X = Ambient temperature (23 to 50°C) Y = On-off ratio of air conditioner for full load conditions (dimensionless i.e. 0-1) R^2= 0.99	-0.8835	+0.0363
4	X = Ambient temperature (23 to 50°C) Y = On-off ratio of air conditioner for No load (no occupancy load) conditions (dimensionless i.e. 0-1) R^2= 0.97	-0.4909	0.021
5	X = Nominal cooling capacity (100-1000 TR) Y = Nominal total electrical power of air conditioner (167-1800 kW) R^2= 1	-31.214	+1.9109
6	X = Nominal cooling capacity (100-1000 TR) Y = Nominal specific electric power of chiller (0.81-0.92 kW/TR) R^2= 1	+0.7629	+0.0003
7	X = Nominal cooling capacity (100-1000 TR) Y = Nominal total specific electric power of AC systems (1.71-1.85 kW/TR) R^2= 1	+1.7061	+0.0002

8	X= Volumetric flow of AHU (0.47-18.88 m^3/s) Y= Power input to AHU motors (0.55-18.50 kW) R^2= 0.94	+1.7241	0.9663
9	X= Volumetric flow of AHU (0.47-18.88 m^3/s) Y= Specific electric power of an AHU (0.98-1.17 kW per m^3/s) R^2= 0.60	+1.5694	-0.033
10	X= Pressurized air delivered from a ventilation unit (0.47-18.88 m^3/s) Y= Power input to AHU motors (0.55-18.50 kW) R^2= 0.98	+0.627	0.9437
11	X= Pressurized air delivered from a ventilation unit (0.47-18.88 m^3/s) Y= Specific electric power of a ventilation unit (0.98-1.17 kW per m^3/s) R^2= 0.60	+1.2602	-0.0193

TABLE 3

ANNUAL ENERGY CONSUMPTION FOR CENTRAL AC THROUGH CONVENTIONAL AND MM-AC.

Sl. No	Particulars	Units	Bangalore	New Delhi	Mumbai	Kolkata	Chennai
1	Annual Cooling Load from vapour compression mode, On time ratio=100 % (1st Time slot: 09:00 to 16:00 h)	kWh/m^2/ year	149.89	407.49	402.94	382.90	492.95
2	Annual Cooling Load from vapour compression mode, On time ratio=100 % (2nd Time slot: 16:00 to 23:00 hrs)	kWh/m^2/ year	86.47	235.09	183.16	174.05	224.07
3	Annual Cooling Load from vapour compression mode, On time ratio=100 % (3rd Time slot: 23:00 to 09:00 hrs)	kWh/m^2/ year	51.88	141.05	146.52	139.24	179.26
4	Annual Cooling Load from vapour compression mode, On time ratio=100 % (whole day	kWh/m^2/ year	288.24	783.63	732.62	696.19	896.28
5	Annual Cooling Load from vapour compression mode, On time ratio=30 % (1st Time slot: 09:00 to 16:00 hrs)	kWh/m^2/ year	44.97	119.90	114.29	116.96	145.20
6	Annual Cooling Load from vapour compression mode, On time ratio=30 % (2nd Time slot: 16:00 to 23:00 hrs)	kWh/m^2/ year	25.94	68.18	61.54	50.13	69.91
7	Annual Cooling Load from vapour compression mode, On time ratio=30 % (3rd Time slot: 23:00 to 09:00 hrs)	kWh/m^2/ year	15.57	42.32	43.96	41.77	53.78
8	Annual Cooling Load from vapour compression mode, On time ratio=30 % (whole day)	kWh/m^2/ year	86.47	235.09	219.79	208.86	268.88
9	Cooling load due to Ventilation mode (1st Time slot)	kWh/m^2/ year	12.93	5.74	10.20	9.38	12.30
10	Mixed Mode Cooling Load (whole day)	kWh/m^2/ year	54.43	116.24	115.70	101.27	135.99
11	Energy fraction of MM-AC vis-à-vis conventional AC	p.u.	0.6295	0.4944	0.5264	0.4849	0.5058

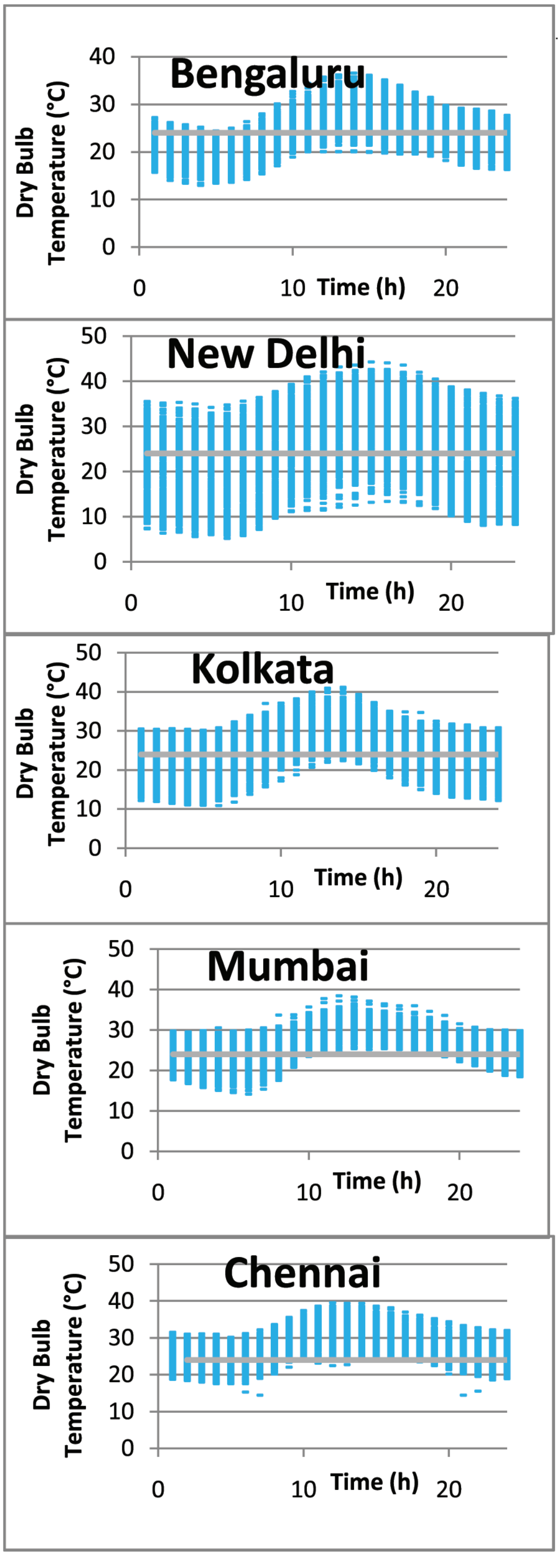

FIG. 5 AMBIENT TEMPERATURES OF MAJOR CITIES OF INDIA.

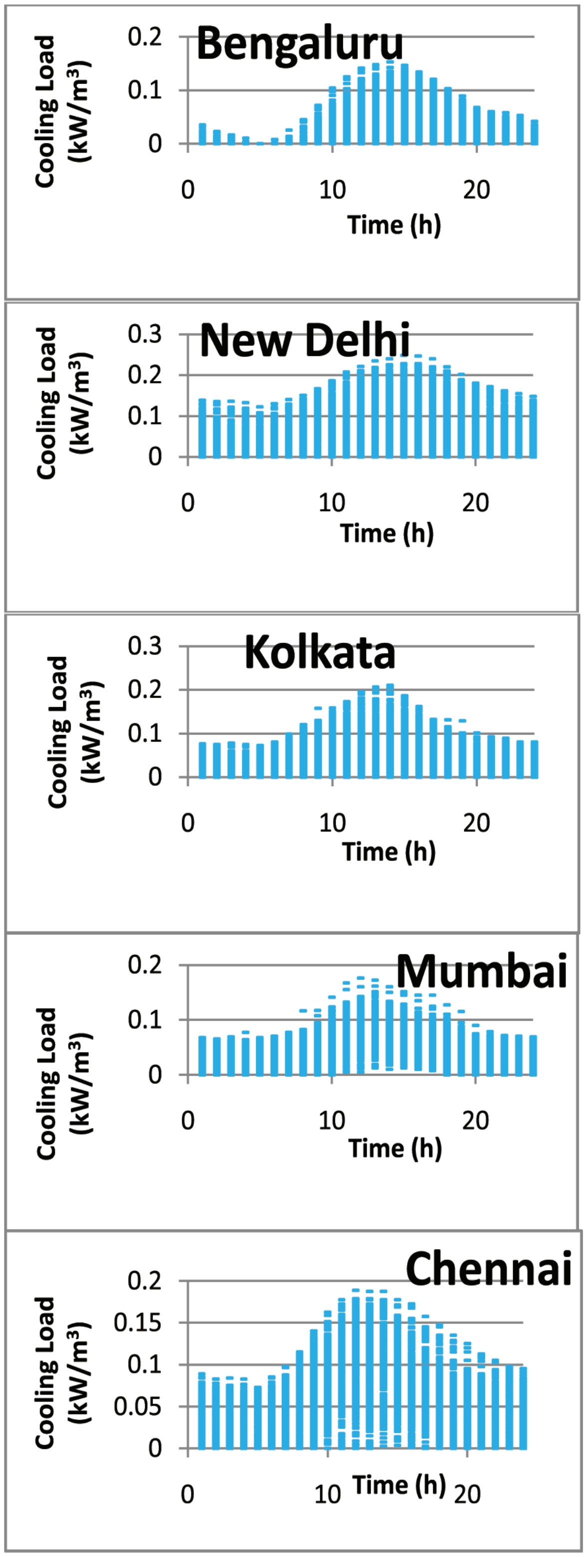

FIG. 6 ANNUAL COOLING LOAD VARIATIONS FOR THE MAJOR CITIES IN INDIA.

The reason for Bengaluru recording low energy consumption is not on account of the energy efficiency but because of the special weather zone. The data for the indicates that the energy consumption attributed to air conditioning is much too high and is need of reduction which can only be achieved through a mix of active and passive systems, i.e., MM-AC.

MM-AC works well when the ambient temperature goes below conditioned air temperature of 23 ˚C or when the ambient temperature is below 23 ºC and the temperature of the conditioned space is higher than 23 ºC. The temperature differential below 23 ˚C is the driving force for the MM-AC. Evaporative cooling brings down the circulation rate of the ventilation fans and hence the energy consumption when the RH is around 40-80 %. When RH is over 80 % chilled water from active AC network will have to be used for reducing the specific power of the ventilation fans.

5. CONCLUSIONS

i. One of the primary methods of energy efficiency improvement in centralized ACs is to have an intelligent control system shifting between the air change with the environment (through ventilation fans) and compression air conditioning (through compressor operation), i.e., the mixed mode AC. MM-AC gives the maximum benefits in the 1st time slot in the day of 09:00 to 16:00 when the AC load is the highest.

ii. Studies for various Indian cities show that the SEC for AC is very high: 86-269 kWh/m^2/year whereas ECBC stipulates only 80-90 kWh/m^2/year for AC. The value of 86 kWh/m^2/year is for Bengaluru is because it has a moderate climate.

iii. Conversion of ACs from the vapour compression cycle only into mixed mode AC systems with evaporative cooling can bring down the SEC by almost 50 %. There is high potential where the ambient temperature is below the comfort temperature and the condition space temperature is above the comfort temperature by 4-5 ºC due to heat accumulation.

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