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Recent Trends In Non-Conventional Space-Conditioning Systems

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Abstract— **Space-conditioning is a dominating energy-consuming service. The demand for heating/cooling/(de)humidification of indoor air is growing with increasing comfort expectations and cooling loads, due to global warming and buildings being designed to squeeze in maximum possible per unit area, owing to space constraints, especially in urban areas, which earlier grew horizontally and now, vertically. Conventional space-conditioning technologies exhibit several clear disadvantages including high energy consumption and electricity peak loads during operation and several negative environmental impacts, as they employ refrigerants. Thus, there is an increasing awareness around the world regarding energy-efficient, environment-friendly space-conditioning systems. The most common economic approach to space-conditioning in buildings is to keep it simplest possible, using locally and easily available materials and technology and leaving nature to do the rest. Various alternative methods of space conditioning have been / are being explored to develop energy-efficient, environment-friendly space-conditioning systems. Three main categories of Non-Conventional Space-Conditioning Systems can be identified as Solar-assisted air-conditioning systems, Earth Tube Heat Exchanger (ETHE) / Buried Tube Heat Exchanger (BPHE) based Space-Conditioning Systems and Other non-conventional space-conditioning systems. There can be varieties in each type depending upon the geographic and climatic conditions for which they are developed, the specific requirements of the system like, work-place, residential building, greenhouse, auditorium, etc. as well as principle on which they work and technology they make use of. This paper aims at studying recent trends in non-conventional space-conditioning systems, their role in energy conservation and their importance in the context of environmental hazards imposed by the conventional systems.**

Keywords - Space-conditioning, air conditioning, earth tube heat exchanger, Green Building, Eco-friendly house.

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I. INTRODUCTION (HEADING 1)

Life cannot exist without energy. All forms of life extract energy from the environment and convert it to forms which can be used. Humans convert energy from forms that are less desirable to those that are more desired i.e. from grass to meat, from wood to heat and from fossil fuels to electricity to meet various needs, which have increased with technological development of the human society. Throughout history, man has developed ways to expand his ability to harvest energy. Looking at how energy sources have changed over time, it is noticed that the age of industrialization and to an even greater extent, the age of technology have accelerated the appearances and exploitation of new energy sources. From primitive man, who had not yet discovered fire, to modern technological man, who has extensively expanded his abilities to harness and use energy for his increasing needs, the usage of energy has increased to as much as about 115 times [1], as shown in Fig.1.

The success of an industrial society i.e., the growth of its economy, the quality of life-style of the population and the society's impact on the environment, is a function of the quantities and types of energy resources it exploits and the efficiency with which it converts potential energy into work and heat. Increasing energy consumption has also been found to closely match societal modernization. The factors which accelerate energy demand include Population growth, Rapid urbanization – increasing population density as well as space constraints, Global warming – a major environmental challenge before the mankind, which calls for serious concern and actions and Fast depleting conventional energy sources, which need conservation and which also add to the problem of global warming because of inbuilt environmental hazards associated with their usage.

Shelter is one of the basic human needs. Residence and Work-places provide this basic need. Energy is an important aspect of the design and planning work in Architecture. Solar Architecture involves developing an energy-aware architectural style. Buildings can have their heating and cooling needs met by the sun in two ways – "Passive" or "Active" [2].

"Passive Solar Architecture" relies on the design or architecture of the building by natural thermal conduction, convection and radiation to ensure climate control. "*Vaastu Shaastra*" – the ancient Indian guide to building a structure, according to specific principles, all of which are based on strong scientific fundamentals, actually advocates what we call – Passive Solar Architecture. It involves incorporating design and construction features such as proper orientation, shapes and sizes of openings like doors, windows, ventilators, etc., use of appropriate, easily available building material, coatings, etc., which optimize utilization of naturally available energy to ensure best possible comfort levels. "Active Solar

Architecture" involves the use of solar collectors, which require an external source of energy. Though in strictly definitive terms, a passive solar building collects stores and distributes solar heat automatically without any mechanical assistance, in practice, "active features" are usually incorporated as they make it possible to control the internal climate and heat distribution a lot more precisely. Also due to space constraints, implementation of all passive features is not possible in urban areas. There has been increase in cooling loads because of climate changes due to global warming effects as well as higher comfort expectations owing to improvements in standard of living as a result of technological advancements. The challenge under these conditions is to minimize cooling loads, which are met with minimum or no utilization of conventional energy sources. Active solar systems use solar panels and solar photovoltaics for heat collection and electrically-driven pumps or fans to transport heat / cold to the living / working area or to storage.

"Hybrid Systems" combine the features of both active and passive systems. In the present scenario, with lots of space and planning constraints, a proper combination of Passive and Active Solar Architecture need to be applied to ensure a comfortable, energy-efficient residence / working place. Some common names given to energy-aware buildings include – Green Building, Passive Home, Eco-friendly House, etc.

Three main categories of Non-Conventional Space Conditioning Systems can be identified –

1. Solar-assisted air conditioning systems,
2. Earth Tube Heat Exchanger (ETHE) / Buried Tube Heat Exchanger (BPHE) based Space Conditioning Systems and
3. Other non-conventional space conditioning systems.

There can be varieties in each type depending upon the geographic and climatic conditions for which they are developed, the specific requirements of the system – like, residential building, work-place, greenhouse, auditorium, etc. as well as the principle on which they are based and the technology they make use of.

II. Literature Review

In a review of the current state of the art regarding earth tubes by Didier Thevenard, using a literature search in scientific journals, the Internet and personal contacts, Definition and Terminology related to Earth tubes, Design Considerations for ETHE, Economics, Potential problems, Climate, Actual system Performance, Commercial products, Design tools, etc. are given [3]. It contains a short list of a few significant publications particularly worth reading as well as an Annotated Bibliography (in alphabetical order), which contains 41 reviews [4]-[44].

More types and configurations of ETHE / BPHE systems can be identified in addition to those identified in this review (as shown in Table 2 and 3 in the succeeding section). The systems considered use air as working medium. Use of water (as in case of Integrated Inbuilt Roof Cooling System[45]) and Heat Pumps – also called Geothermal / Geo-exchange systems, which work on the basis of Vapour Compression Refrigeration Cycle and use air, water or anti-freeze refrigerant as working medium [46], have not been mentioned. The Review had been prepared in September, 2007. The web-sites mentioned in the review have got updated and they contain details about some heat pump systems, now. The presentations / papers mentioned have been referred.

Some points worth noting from this review are :

- System performance is often not well documented. In the particular case of simulation or design tools, validation of the models with data collected over significant periods (e.g., at least a year) is generally lacking.
- Even when monitoring data is provided, studies are often incomplete. For example some papers report that lower temperatures are achieved if the airflow is reduced, but that doesn't address the issues of how much energy can be displaced.
- Similarly, many papers do not provide a comprehensive summary of the energy required to move the air through the pipes. Long-term thermal imbalance in the soil around the pipes is rarely addressed.

The Performance of a single-pass ETHE made up of 50m long MS pipe having 10cm nominal diameter and 3mm thickness was studied [47] and an axi-symmetrical, time dependent finite element method (Galerkin Method) with triangular elements for developing a mathematical model of the ETHE using PDE2D (Sewell 2002) shows fair confirmation with actual performance observations of the ETHE [48].

Most of the Numerical models developed and simulations attempted for ETHE systems are based on finite element method. Also, the configurations of ETHE considered have long, large diameter tubes, such as :

Numerical model for Design and Simulation of a Hybrid Ventilation System made up of two 60m long, 1m-diameter galvanized steel grooved ducts for a circus building in Montreal [49].

Numerical model to predict energy conservation potential of earth-air heat exchanger system and passive thermal performance of building, using numerical techniques of finite difference techniques and FFT (Matlab) which is validated for an 80m Earth Tunnel [50] (Reviewed by Didier Thevenard, comments given point no. 22, section 3.3 [1]).

Some references on experimental works are also found, such as the one on an application of earth tubes to heat and cool a greenhouse in the North-West part of India, in an arid climate. The paper is mostly experimental and reports that the system is able to heat the greenhouse during cold nights and keep it significantly cooler during hot days [51].

The study of the use of shorter diameter tubes having lesser length, with turbulent flow inside the tubes – to enhance the heat transfer rates for AIR-Based ETHE / BPHE systems does not feature in any of the papers.

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Ground-coupled Heat Pumps (GHP) – also called Geothermal Systems and Geo-exchange systems, which work on the principle of Vapour Compression Refrigeration Systems are used in the US, European countries like Denmark, UK, Sweden, etc. Various configurations of these systems are possible, which use air, water or anti-freeze refrigerant as working medium, which can be open loop, closed loop or combined systems, in which pipes (GI or plastic pipes can be used) can be laid horizontally – either parallel to each other or radially – or vertically in the ground for various applications like, residential buildings, office buildings, greenhouses etc. They involve use of refrigerants and have a compressor, a condenser, an expansion device, and an evaporator like a refrigerator, and also include a reversing valve to allow both heating and cooling. A fair idea about the research in Vertical U-Tube WSHPs can be obtained from the literature review of thesis by Steven P. Rottmayer [52].

The principal of operation and configurations of Heat Pumps are different from those of ETHE / BPHE based systems, which are much simpler and economical compared to Heat Pumps [53].

Cooled ceiling technique is getting popular in many European countries and has found its use in many office buildings as an air-conditioning alternative as given by Mertz (1992) and Wilkins (1992). A cooled ceiling can have many variations, one of which is horizontal plate type. In this type of design, specifically made cooling panels are installed as part of a false ceiling, through which cold water flows and extracts heat from the room. Some manufacturers also produce ceiling panels that function as air ducts, through which ventilation air is preheated by internal room heat before entering the room through air diffusers. Various ventilation systems can be combined with the water ceiling system to provide the required outside air and latent cooling. Usually, separate heat devices are located conventionally underneath the windows. In some cases, the ceiling panels are also used for heating purposes. The cooled ceiling system has some unique characteristics. Among other things, the horizontal panels will extract heat by both radiation and convection. On the other hand, the existence of the cooled panel surface will lower the radiant temperature in a room. Therefore, special cooling load calculation methods will be required for the design of this system [45].

In one research, a new methodology was developed which combined the thermal dynamic modeling of building elements and the ceiling panels with each other and integrated the thermal comfort indices in the calculation procedure. For this purpose, a computer program called ACCURACY, given by Chen et. el. (1998) was enhanced [45].

The water used for cooling is circulated through cooling panels installed in the false ceiling. In an Integrated Inbuilt Roof Cooling System (IIRCS), water is circulated through piping embedded in the roof [45].

In the Thermal Design Optimization of IIRCS [45, 54, 55], it is found that embedding piping on the roof, as close to the roof surface as possible would give better system configuration. This is due to the fact that the heat being conducted from the roof is trapped before it reaches downwards to add to the room temperature. Hence, embedding piping system in the water-proofing would be better.

Circulating cool / hot air from AIR-Based ETHE / BPHE through ducting mounted in false ceiling can be done.

Roof Cooling Techniques : According to an ASHRAE Model, roof contributes about 46% of the total heat load to be handled by the cooling system [56]. Means of Roof Cooling are thus important, though the fact is yet to get enough attention. There are various Passive means of Roof Cooling, such as high Emissivity roof coatings, Cool Metal Roofs, Increasing Solar Reflectance of Fibreglass Asphalt Shingles, Increasing Solar Reflectance of Clay tiles, etc. [57].

Passive means, in addition to raising initial cost of construction in most cases, are not sufficient to meet the requirements of cooling imposed by the prevailing conditions of space constraints, which impose restrictions on orientations and sizes of openings, lighting and air circulation, etc. as well as raising temperatures, especially in urban areas and / or in hot and dry climatic zones (Dry Bulb Temperature > 30^{o}C, Relative Humidity < 55%) [58]. Dependence on active means has become an unavoidable necessity, which has to be minimized using energy efficient, environment friendly means and methods.

III. Types of Non-Conventional Space Conditioning Systems

From the study of various Non-Conventional Space Conditioning Systems, three categories of such systems can be identified, a brief description of which is as follows:

A. *Solar Assisted Space Conditioning Systems*

These systems use the energy of the sun to heat, cool, light and power buildings. They use solar heat to drive a heat-driven chiller or dehumidifier, such as ab- or adsorption chillers, and desiccant evaporative cooling systems. A well designed solar assisted air-conditioning system produces cooling with considerably less electricity demand than conventional air-conditioning systems. Furthermore, the working fluids used in sorption chillers and desiccant rotors will not contribute to global warming, contrary to most working fluids in conventional compression chillers. It promotes a reduction of primary energy consumption and electricity peak loads due to cooling. These systems include solar collectors on the one hand, and a heat-driven chiller / dehumidifier on the other.

Solar-assisted air conditioning systems studies are very important. Experience shows that many problems of real operation rise rather on a system level than on the level of single components. Important issues for system studies are control, primary energy savings and economy of the installations [3]. Table:1 shows a summary of types, characteristics and prospects in various solar assisted space conditioning systems.

B. *Earth Tube Heat Exchanger (ETHE) / Buried Tube Heat Exchanger (BPHE) based Space Conditioning Systems*

It is a well-known fact that while ambient temperatures are subjected to diurnal, seasonal and annual fluctuations, temperatures of the soil beyond a certain depth remain virtually

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constant. Though these variations do occur, amplitudes of fluctuations in the deep soil temperatures remain much smaller than those at the surface. So, deeper layer of the soil can be used as both – heat sink (during summer) and heat source (during winter). BPHE / ETHE Systems are low cost, reliable and easy-to-maintain systems based on this concept. The coolant / heating fluid may be air or water or any other suitable fluid and it is circulated with the help of a blower – when air is used – or a centrifugal pump – when water / liquids are used – through an underground piping system – to reject the heat gained from the thermal load on the structure being cooled, or – to gain heat from the ground to heat the structure [45].

Fig. 1 shows a typical Earth-Air Heat Exchanger (EAHE) system, in which air is circulated through piping laid in the ground and after being heated or cooled, as per the requirement / season, the air is circulated in the space to be conditioned [47].

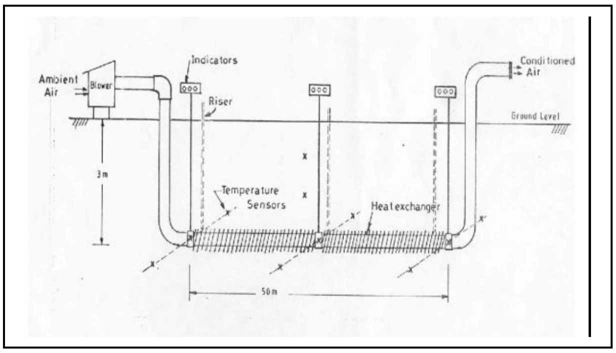

Figure 1. A typical single-pass EAHE system [47]

Figure 2 shows the working of Heat Pumps – commonly known as Geo-exchange or Geothermal systems, which are double circuit systems and work on the principle of Vapour Compression refrigeration systems and are widely used in the USA, Canada and European countries like Germany, Denmark, Finland, Sweden, etc. [52].

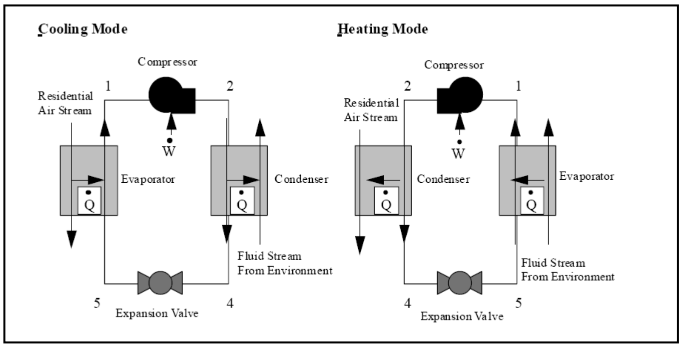

Figure 2. Heat Pumps [52]

As mentioned earlier, roof contributes about 46% of the total heat load to be handled by the cooling system [56]. Means of Roof Cooling are thus important, though the fact is yet to get enough attention. Passive means include use of high Emissivity Coatings, which can add considerably to the cost of the building, high reflectivity tiles on the roof, etc. and are insufficient to meet the need of thermal cooling imposed by the prevailing conditions of space constraints. Hence, active means, using external power supply, have become necessary.

In an ETHE / BPHE based Integrated Inbuilt Roof Cooling System (IIRCS), water circulated in the piping embedded in the roof – Roof Piping System (RPS) of a building takes away the heat load due to incident solar radiation as well as internal load due to occupancy, equipments, etc. and gets cooled by the BPHE laid in the ground before getting recirculated in the RPS [45].

An IIRCS is a single circuit, simple, low cost, low maintenance active solar architecture system, which has good potential for space conditioning in hot, dry regions [55]. Figure 3 shows a schematic diagram of an IIRCS.

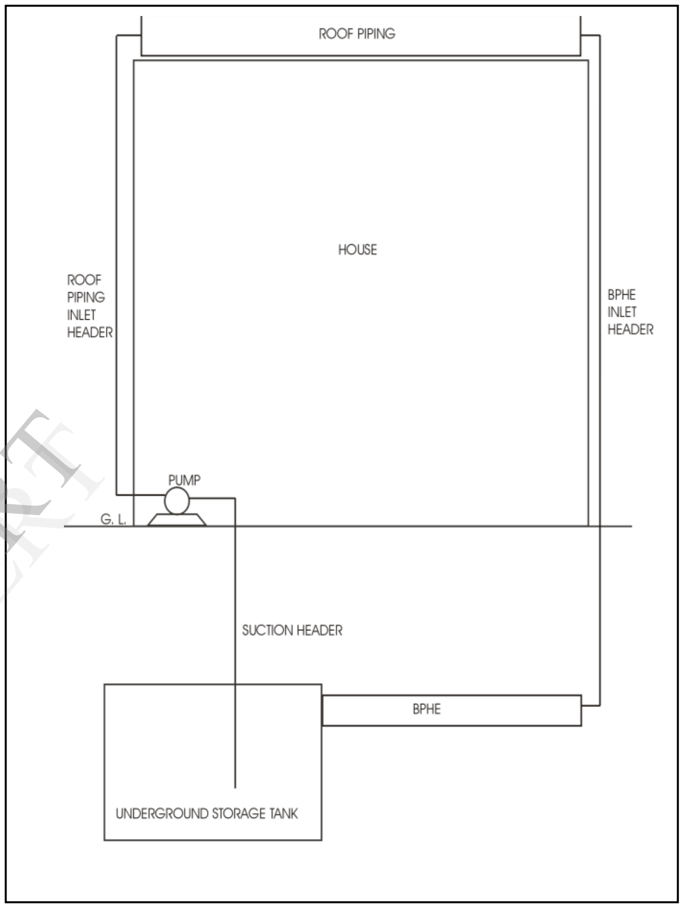

Figure 3. Schematic Diagram of Integrated Inbuilt Roof Cooling System [45].

Tables 2, 3, 4 and 5 show classification of ETHE / BPHE based space conditioning systems, the outline of the classifications, summary of characteristics of these systems and their future prospects, along with the related operative, economic and environmental aspects, respectively.

C. Other Non-Conventional Space Conditioning Systems

- REGENERATIVE HEAT EXCHANGERS: In a regenerative heat exchanger (sometimes called a capacitance heat exchanger) the hot and cold fluids pass alternately across a matrix of material; the matrix

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is heated up by the hot fluid then cooled down by the cold fluid so that the process is cyclic. A more recent use of Regenerative Heat Exchangers is in heat recovery to and from buildings – as shown in the block diagram in fig. 4.

- THERMAL WHEEL : It is a Rotary Regenerator, in which a matrix of material is mounted on a wheel which is rotated slowly through the hot and cold fluid streams – used in heat recovery is in air-to-air applications for buildings – as shown in the block diagram in fig. 5.

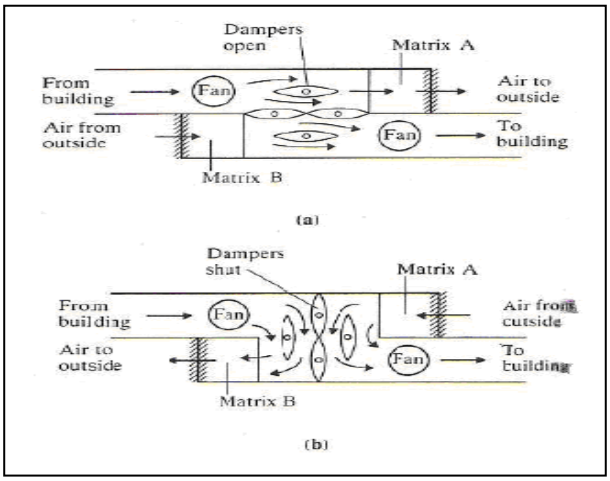

Figure 4. Regenerative Heat Exchangers

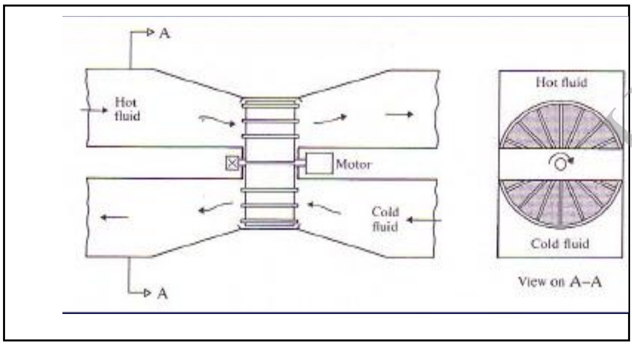

Figure 5. Thermal Wheel

IV. SOME IMPORTANT FACTS

USA has the largest per capita energy consumption in the world [59]. India ranks sixth in the world in terms of energy demand accounting for 3.5% of world commercial energy demand in 2001 [60]. The per capita energy consumption in India is less than that of most countries (290 kg per capita), even less than that of neighbouring Pakistan (293 kg per capita) as per the records in April, 2001 at the Ministry of Environment and Forests [61], owing to high population. As per the Energy and Resources Institute, New Delhi, by 2030, the population of India will become more than that of China and by 2050, India will consume 1/3rd of the total global energy demand [62].

All the three sectors of energy consumption – namely, Transportation, Industry and Residential and Commercial sectors, especially the latter one have space conditioning as one of their major energy consumption areas [59]. Energy conservation in space conditioning is thus important. There is an increasing awareness around the world regarding much needed energy-efficient, environment friendly space conditioning systems. Such systems become more important in developing countries like India, which have acute power shortage problems, especially if they are cost-effective [63]. Attempts to encourage Solar Architecture are an indication of this fact [2].

V. CONCLUSIONS

Solar-assisted systems have some draw-back or the other each, such as low efficiency of collector type system, capacity, efficiency and economic limitations of cooling and dehumidification systems, and use of non-environment friendly ammonia and low efficiency of 2-phase, 2-component jet cycle chiller, which necessitate further research and development work. ETHE / BPHE based systems show good potential as regards simplicity of construction, easy maintenance and operation, etc., especially single-circuit EAHE and IIRCS systems.

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Table – 1 : Summary of types, characteristics and prospects in various Solar-assisted Space Conditioning Systems

Solar Collectors [3]	**Cooling and Dehumidification Technologies** [3]	**Other Solar Assisted Air-Conditioning Technologies** [3]
Types : Parabolic trough collectors Stagnation-proof transparently insulated Flat Plate solar collector (STATIC).	Types : Absorption Chillers Adsorption Chillers Desiccant Systems	Other Solar-assisted Air-Conditioning Technologies : Many heat-driven cycles can be tried – one of them being Jet Cycle.
To achieve primary energy savings. The challenge : the efficiency of sorption systems – in particular absorption systems. Benefits from high drive temperatures. Collectors that achieve high temperatures (with an acceptable efficiency) tend to be more expensive than conventional flat plate systems. Not designed for a certain application but for a certain operation temperature level.	**Absorption Chillers** : Main challenges in their wide-spread application– Large-scale applications machines available, but there is also a demand for smaller solar-assisted air-conditioning systems; LiBr absorption chillers need a cooling tower Efficiency and capacities are small at low driving temperatures More expensive collector types (e.g. vacuum tubes, CPCs) are required in combination with absorption chillers to guarantee a sufficient efficiency.	2-phase/2-component jet-cycle chiller - NH_3/H_2O jet cycle chiller, using heat < 80ºC as driving energy, suitable for small commercial applications. Its modeled efficiency is slightly above 0.2. It has little moving parts and provides sensible cooling.
	Adsorption chillers : They have a higher efficiency at low driving temperatures than absorption chillers. Adsorption technology has a few weaknesses: They are more expensive per kW cooling capacity than absorption chillers; There is a limited market choice (very few manufacturers); The process has a cyclic nature, which requires more effort in design and control; The machines are big and heavy.	
	Desiccant Systems : Desiccant evaporative cooling (DEC) systems have the advantage that they can treat latent loads separately. They can replace a conventional ventilation system in which the cooling / dehumidification function is realized by a conventional electrically driven vapour compression chiller. There is little research on solid desiccant wheels or DEC systems. Liquid desiccant systems can be cheaper than solid desiccant wheels, if current market-available products are compared.	

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Table – 2 : Classification of various ETHE / BPHE based Space Conditioning Systems.

<table>
<tr><th colspan="5">Working Medium</th><th colspan="7">Working principle</th><th colspan="6">Circulation</th><th colspan="2">Laying of Pipes [52]</th></tr>
<tr><td colspan="2">Air-based</td><td colspan="3">Water-based</td><td colspan="4">Single Circuit Systems</td><td colspan="3">Double Circuit Systems</td><td colspan="2">Open Loop Systems</td><td colspan="3">Closed Loop Systems</td><td>Comb-ined Systems</td><td rowspan="2">Hori-zontal Loop</td><td rowspan="2">Verti-cal Loop</td></tr>
<tr><td>Earth-Air Heat Ex-changer (EAHE)</td><td>Air Source Heat Pumps (ASHP)</td><td>Integrated Inbuilt Roof Cooling System [45]</td><td colspan="2">Heat Pumps [53]</td><td colspan="2">Open Loop Systems</td><td colspan="2">Closed Loop Systems</td><td colspan="3">Heat Pumps [52] : working is similar to that of Refrigerator, using a vapor compression cycle for operation. They have a compressor, a condenser, an expansion device, and an evaporator like a refrigerator, and also include a reversing valve to allow both heating and cooling.</td><td>Air-based</td><td>Water-based</td><td>Air-based</td><td>Water-based</td><td>Refrige-rant / Anti-freeze solution based</td><td>Air-based</td></tr>
<tr><td>Open-Loop System</td><td>Closed Loop System</td><td>Water is circulated through piping laid in the roof, which gains the heat – incident solar heat as well as internal heat due to occupants, appliances, windows, doors, walls, etc. – and gets cooled by a heat exchanger e.g. BPHE before getting recirculated through the Roof Piping System (RPS).</td><td>Water Source heat pump (WSHP)</td><td>Refri-gerant-based / Anti-freeze Solution – based</td><td>Air-Based (EAHE)</td><td>Water – based (Pond or Lake Loop Systems)</td><td>Air-based (ASHP)</td><td>Water-based IIRCS, WSHP</td><td>Air-based : Air Source Heat Pumps (ASHP) – Closed Loop systems, they exchange heat with the environment by circulating ambient air through an air-to-refrigerant heat exchanger.</td><td>Water-based (WSHP): Water-to-refrigerant heat exchanger transfer heat to the environment with a water-to-refrigerant heat exchanger. These are also called Geothermal Heat Pump Systems / Geo-exchange Systems / Ground Heat Pumps.</td><td>Refrigerant-based / Anti-freeze Solution – based: They use Refrigerant / Anti-freeze solution as working medium. They are used in very cold regions, where temperatures fall down to around or below 0^oC.</td><td>EAHE</td><td>Pond or Lake Loop Systems : economical to install when a body of water is available. Eliminates excavation costs. Coils of pipe are simply placed in the bottom of the pond or lake.</td><td colspan="3">Heat Pumps : Water-based systems can be Pond or Lake Loop Systems.</td><td></td><td>Radi-al or Lateral</td><td></td></tr>
<tr><td colspan="3">Applications</td><td colspan="17">Residential Buildings, Office Buildings, Auditorium Buildings, Circus Buildings, Greenhouses, Animal Husbandry Farms, Animal Dwellings, etc.</td></tr>
</table>

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Table – 3 : Outline of various ETHE / BPHE based Spaced Conditioning systems.

ETHE / BPHE BASED SPACE CONDITIONING SYSTEMS

WORKING MEDIUM	WORKING PRINCIPLE		CIRCULATION			LAYING OF PIPES		
	SINGLE CIRCUIT	DOUBLE CIRCUIT	OPEN LOOP	CLOSED LOOP	COMB -INED	HORIZONTAL		VERTI-CAL
						RADIAL	LATERAL	
AIR – BASED								
EARTH-AIR HEAT EXCHANGER (EAHE)	√		√			√	√	
AIR SOURCE HEAT PUMP (ASHP)		√		√		√	√	
WATER – BASED								
INTEGRATED INBUILT ROOF COOLING SYSTEM (IIRCS)	√			√			√	
HEAT PUMPS								
WATER SOURCE HEAT PUMP (WSHP)		√	√	√	√	√	√	√
REFRIGERANT / ANTI-FREEZE SOLUTION BASED HEAT PUMP		√		√		√	√	√

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Table – 4 : Summary of Characteristics in various ETHE / BPHE based Space Conditioning Systems.

Criteria for Comparison	Earth-Air Heat Exchanger (EAHE) System	Heat Pumps [52]			Pond or Lake Loop Systems [52]	Integrated Inbuilt Roof Cooling System [45]
		ASHP	WSHP	Refrigerant / Anti-freeze solution based Heat Pumps		
Principle of working	**1. Temperatures of the soil beyond a certain depth remain virtually constant. So, deeper layer of the soil can be used as both – heat sink (during summer) and heat source (during winter).** **2. Ambient air is passed through the ETHE and conveyed to the space to be conditioned by ducting.**	1. Temperatures of the soil beyond a certain depth remain virtually constant. So, deeper layer of the soil can be used as both – heat sink (during summer) and heat source (during winter). 2. Working is similar to that of Refrigerator, using a vapor compression cycle for operation. They have **a compressor, a condenser, an expansion device, and an evaporator** like a refrigerator, and also include a reversing valve to allow both heating and cooling.			Pond or Lake located nearby can be used as Heat source or Heat Sink. Piping is laid at the bottom of the source. Working medium circulates through the piping and heat is lost or gained – as per the design of the system.	**Water is circulated through piping laid in the roof, which gains the heat – incident solar heat as well as internal heat due to occupants, appliances, windows, doors, walls, etc. – and gets cooled by a heat exchanger e.g. BPHE before getting re-circulated through the Roof Piping System (RPS).**
		Exchange heat with the environment by circulating ambient air through an air-to-refrigerant heat exchanger.	Water-to-refrigerant heat exchanger transfers heat to the environment with a water-to-refrigerant heat exchanger.	Use Refrigerant / Anti-freeze solution as working medium, otherwise, similar to WSHPs.		
Working Medium	**Air [47]**	Air [52]	Water [52]	Refrigerant / Anti-freeze solution [52]	Air or Water or Anti-freeze solution. [52]	**Water**
Laying of Pipes – Horizontal (Radial / Lateral) / Vertical, single pass / multi-pass.	**Horizontal – lateral (preferred), single or multi-pass (as per space availability).**	Horizontal – radial or lateral (preferred) configurations possible.	Horizontal – radial or lateral (preferred), as well as Vertical configurations possible. [53]	Horizontal – radial or lateral (preferred), as well as Vertical configurations possible. [52]	Horizontal – radial or lateral (preferred) configurations possible. [52]	**Horizontal – lateral (preferred), single or multi-pass, as per space availability.**
Buried Depth (typical values)	**1.5m – 3m [45].**	1.5m – 3m.	1.5m-3m : for horizontal laying of the pipes. 20m-150m for vertical laying of pipes. [53]	1.5m-3m : for horizontal laying of the pipes. 20m-150m for vertical laying of pipes. [52]	At the bottom of the pond or lake – as the case may be. [52]	**1.5m-3m**
Pipe Material	**MS Pipes [47], Hume Pipes [52, 62]** **HDPE can be used – more pipe length and space requirements, but economical and corrosion-resistant.**	Smooth-walled, rigid or semi-rigid plastic (e.g. PVC used in Europe, but HDPE is better) or metal pipes (Copper or GI).	Smooth-walled, rigid or semi-rigid plastic (e.g. PVC used in Europe, but HDPE is better) or metal pipes (Copper or GI).	Smooth-walled, rigid or semi-rigid plastic (e.g. PVC used in Europe, but HDPE is better) or metal pipes (Copper or GI).	HDPE Pipes. [52]	**For RPS : HDPE or Rigid PVC Pipes** **For BPHE : Generally, G. I. Pipes – less pipe length and space requirements, but costly and problem of corrosion has to be dealt with. HDPE can be used – more pipe length and space requirements, but economical and corrosion-resistant.**
Pipe Size / Specifications and Spacing	**Large diameter Hume Pipes (concrete pipes) and M.S. pipes [47] have been used (e.g. 1m dia. Hume pipes [45, 63]).** **It would be better to use more number of smaller diameter pipes – GI, MS or HDPE pipes.**	100 to 450mm (4 to 18 inch) diameter, smooth-walled, rigid or semi-rigid plastic (e.g. PVC, HDPE) or metal pipes (Copper or GI).	100 to 450mm (4 to 18 inch) diameter, smooth-walled, rigid or semi-rigid plastic (e.g. PVC, HDPE) or metal pipes (Copper or GI).	100 to 450mm (4 to 18 inch) diameter, smooth-walled, rigid or semi-rigid plastic (e.g. PVC, HDPE) or metal pipes (Copper or GI).	Small diameter HDPE Pipes – e.g. ¾" or 1". [52]	
Single Circuit or Double Circuit	**Single circuit.**	Double Circuit [52]	Double Circuit [52]	Double Circuit [52]	Double Circuit. [52]	**Single Circuit.**
Open Loop or Closed Loop	**Open Loop.**	Open Loop or Closed Loop – as per the design.	Open Loop or Closed Loop – as per the design.	Open Loop or Closed Loop – as per the design.	Open Loop or Closed Loop – as per the design.	**Closed Loop.**
Applications	**Residential Buildings, Office Buildings, Auditorium Buildings, Circus Buildings, Greenhouses [51] , Animal Husbandry Farms, Animal Dwellings [45], etc.**	Residential Buildings, Office Buildings, etc.	Residential Buildings, Office Buildings, Greenhouses, etc.	Residential Buildings, Office Buildings, etc. at places where temperatures are very low – around or less than 0^{o}C.	Residential Buildings, Office Buildings, Farms, Greenhouses, etc.	**Residential Buildings, Office Buildings, etc. in hot, dry regions.**

Table – 5 : Prospects of various ETHE / BPHE based Space Conditioning Systems.

Criteria for Comparison	Earth-Air Heat Exchanger (EAHE) System [47, 53]	Heat Pumps [52]	Pond or Lake Loop Systems [52]	Integrated Inbuilt Roof Cooling System [45]
Simplicity of construction.	**Simple construction.**	More complex in construction, since they work on the principle of Vapour Compression Refrigeration System and hence they have Compressor, Expansion Device and Evaporator. Also, these are double circuit, closed loop systems and they require refrigerant for their operation.	More complex in construction, since they work on the principle of Vapour Compression Refrigeration System and hence they have Compressor, Expansion Device and Evaporator. Also, these are double circuit, closed loop systems and they require refrigerant for their operation.	**Simple construction.**
Ease in Installation.	**Easy to install.**	Comparatively, more difficult to install.	Comparatively, more difficult to install.	**Easy to install, but have to be installed in newly constructed buildings only, not in existing ones.**
Capital Cost.	**Less than or almost equal to that of Convention Space Conditioning Systems.**	Higher capital cost.	Higher capital cost.	**Less than or almost equal to that of Convention Space Conditioning Systems.**
Maintenance Cost.	**Much less maintenance cost compared to conventional systems.**	Maintenance cost similar to those of conventional systems, since components like compressor are there and refrigerant is also required.	Maintenance cost similar to those of conventional systems, since components like compressor are there and refrigerant is also required.	**Much less maintenance cost compared to conventional systems.**
Operating Cost.	**Less compared to conventional systems.**	Less compared to conventional systems.	Less compared to conventional systems.	**Much less compared to those of conventional systems, lesser than EAHE, Heat Pumps and Pond or Lake Loop Systems.**
Are they Environment Friendly ?	**Yes.**	No – refrigerant used.	No – refrigerant used.	**Yes.**

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