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DEVELOPMENT OF A SOLAR POWERED ADSORPTION CHILLER

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ABSTRACT

Heat driven cooling technologies like vapour absorption and adsorption systems are environmentally friendly. Use of thermal compression in these systems saves precious and fast-depleting fossil fuel resources. Solar energy and low-grade waste heat can be effectively used in running these cooling systems. The present work focuses on the development of a solar-powered vapour adsorption based cooling system, which have the potential to be a carbon-free alternative to vapour compression cooling cycles, especially for meeting domestic and office space requirements. Poor heat and mass transfer properties of the adsorbents lead to bigger sizes and more cost. Use of thin beds along with integrally finned tubes has been adopted in this work to augment the heat transfer through the bed. A temperature distribution profile of the silica gel bed has been developed through finite difference method, to have an in-depth study of the heat transfer process during desorption. A test unit of adsorption chiller has been developed for round the year parametric study with a heat pipe based evacuated tube solar water heater installed on the roof.

Keywords: Solar energy, Adsorption cooling, Natural refrigerants, Heat exchangers.

1. INTRODUCTION

The history of cooling dates long back. In olden days, cooling was achieved by natural means such as ice, or evaporative cooling. In western countries, ice was harvested in winter months and stored in ice-houses to satisfy the need for cooling in the summer season. In India, during the Mughal regime, it is believed that ice was obtained from nocturnal cooling. Evaporative cooling was, and continues to be used to get cold water by storing it in earthen pots [1].

With the beginning of the Industrial revolution, artificial means of cooling came into existence. It is generally agreed that William Cullen devised the first refrigerating machine in the year 1775 [1], which was based on the principle of vapour compression and capable of producing a small quantity of ice in the laboratory. In the following years, scientists and technologists came up with improved systems of cooling that were based on vapour compression; as well as vapour absorption and gas/air cycles.

The decade of 1930s witnessed a revolution in cooling technology with the development of synthetic refrigerants such as freons (R-11, R-12, R-22, R-134, etc.), which greatly increased the coefficient of performance of vapour compression based systems, thus playing a major role in establishing the dominance of vapour compression systems in home and office applications.

Vapour compression systems have the advantages of being efficient, relatively inexpensive and compact, and easy to setup and maintain.

However, synthetic refrigerant based vapour compression systems have two major environmental issues. The substances such as CFCs, HCFCs, etc. which are used as the working fluid in most vapour compression systems have been shown to be responsible for ozone layer depletion as well as contributing to global warming. HFCs are a popular class of refrigerants which do not contribute to ozone layer depletion, but have high global warming potential (GWP). Because of their serious environmental implications, these substances are required to be phased out as per the obligations of the Montreal Protocol (1987) and the Kyoto Protocol (1997). Moreover, vapour compression systems use compressors that consume huge amount of electrical energy, thus aggravating the global energy crisis by depleting the precious fossil fuel reserves as well as causing environmental pollution in the process. The need for a switch over to green and sustainable alternatives is, thus, evermore pressing.

Heat-operated cooling systems, such as those based on vapour absorption and vapour adsorption, provide a promising alternative to the conventional vapour compression systems. Because of the absence of mechanical compressors as well as the use of natural refrigerants, these systems do not contribute to depletion of fossil fuels, global warming, or ozone layer depletion. Among heat-operated systems, some vapour absorption systems have been in recent use in industries, being driven by industrial waste heat, solar energy etc.

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However, they are found to be more suitable for larger systems (> 30 TR capacity) [2]. Compact, maintenance-free adsorption systems may cater to the cooling needs of domestic and office spaces, if properly developed. Compared to vapour absorption systems, vapour adsorption systems have some other advantages also. The latter are not prone to crystallisation, which is a particular problem with absorption systems utilising lithium bromide-water. They can be operated with low temperature heat sources and are less sensitive to fluctuation of driving source temperature. This makes them the technology of choice when solar energy is used.

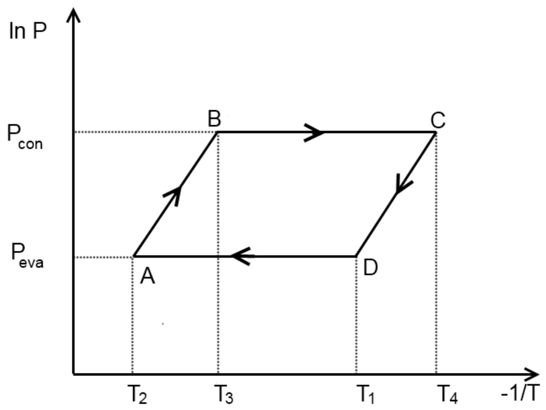

Fig. 1. Adsorption cycle in Clapeyron diagram

2. ADSORPTION REFRIGERATION SYSTEM

Adsorption refrigeration technology has been reported to be in use as early as in the 1920s. In the United States, an adsorption chiller powered by the hot gases from burning coal and utilising sulphur-dioxide as refrigerant was used to air-condition railway carriages [3]. The development of adsorption based systems progressed comparably to vapour-compression systems for some years. However, the development of better and smaller compressors from 1920s and application of synthetic refrigerants like freons during 1930s pushed the development of adsorption systems to the backseat. With the post-depression boom in the economy well underway during this period, refrigerators became a household appliance in the western countries. Due to their compact construction, high efficiency and safe operation, vapour compression technology came to dominate the commercial market and interest in adsorption refrigeration technology declined. After the oil crisis of the 1970s, interest in renewable energy technology resurfaced. Adsorption refrigeration systems were developed with the objective of rational use of energy and were thus powered either by solar energy or by waste heat. As the ecological problems faced by the use of CFCs and HCFCs came to be highlighted during the 1990s, research into new adsorbent-adsorbate pair as well as better methods of heat and mass transfer began in order to improve the efficiency of these systems.

Adsorption refrigeration systems rely on successive adsorption and desorption of refrigerant in a cycle to produce the cooling effect. Fig 1 shows the steps involved in an adsorption refrigeration system. DA shows the constant pressure adsorption of the refrigerant on the desiccant surface, which triggers evaporation of the refrigerant in the evaporator, producing cooling effect. When the surface of the desiccant pores gets saturated with refrigerant molecules, heat is supplied to the desiccant increasing its temperature, as shown by AB. As a result of this, pressure in the chamber rises to the condenser pressure and desorption starts which is shown by the BC. The desorbed refrigerant goes to the condenser, loses heat, makes way to the evaporator and pressure reduces to the evaporator pressure as illustrated by CD. The refrigerant again gets evaporated; producing cooling effect and simultaneously adsorption takes place in the adsorber. The cooling achieved in this essentially fixed bed single chamber system is discontinuous, although quasi-continuous cooling can be obtained by using two adsorbent beds operating in cycles out of phase with each other. The process described above can be compared qualitatively with the evaporation, compression, condensation, and expansion stages, respectively, of a conventional vapour compression system [4]. Adsorption refrigeration systems, however, are heat driven unlike vapour compression systems which make use of mechanical work to drive the refrigeration cycle.

2.1 Solar powered Adsorption Refrigeration Systems

Solar powered adsorption systems make use of solar radiation to effect desorption of the refrigerant from the desiccant pores. Solar energy may be used directly to heat up the adsorbent bed as in the case of some fixed-bed adsorption systems that operate in 24-hour-long cycles; or indirectly, by making use of solar collectors to heat up water which is then cycled through the adsorbent bed. In contrast to systems powered by conventional energy sources, solar powered systems have no adverse environmental effects. Refrigeration and air conditioning systems powered by solar radiation have an implicit advantage that the peak demand for cooling is in phase with the availability of solar energy. Also, the heat collection arrangement used in these systems can be extended to provide hot water in winter months in residential installations. Solar adsorption refrigeration systems have the ability to operate with low and fluctuating temperature heat reservoirs which makes the use of simple flat-plate and evacuated-tube collectors possible. In domiciliary as well as office use, safety and low maintenance requirements are a major factor. This gives adsorption systems a comparative edge over absorption systems which may be prone to hazardous chemical leaks or corrosion of parts. Consequently, adsorption systems have a longer service life.

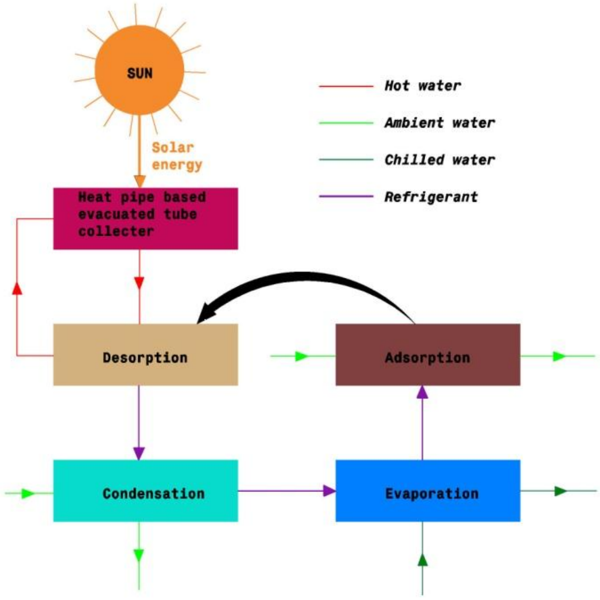

Fig. 2. Block diagram of solar adsorption cooling

Low grade waste heat is also an effective source to drive adsorption cooling systems. Waste heat accounts for 50–70% of fuel consumption in thermal power plants and 50–60% in internal combustion engines [5] and if discarded to the surrounding represents not only a loss of the fast-depleting primary energy resources as well as causing thermal pollution. The use of this waste heat to power adsorption cooling systems improves the efficiency of the overall system.

3. STATE OF THE ART

Work on different adsorbent-adsorbate pairs like activated carbon - methanol/ ethanol/ ammonia, zeolite - water, silica gel - water has been reported in literature [6]. Initial works mainly centred on production of ice by solid adsorption refrigeration [7]. Interest on solar adsorption refrigeration has also peaked up during recent years. Research is being carried out around the globe in order to improve the solar-powered adsorption system COP and/or extend the operating temperature ranges so that very low-grade heat can be used to operate the system or low temperatures can be obtained using the same low-grade heat input. Critoph [8] pointed out the performance limitations of adsorption cycles for solar cooling. Pons and Poyelle [9] worked on advanced cycles for adsorption machines. Meunier et al. [10] worked on determining thermal and mass diffusivity of packed silica gel beds. Work on multi-stage, composite adsorbent and hybrid systems (to develop commercially viable alternative) have also been started [11-13]. The area of focus includes improvement in heat transfer properties and thermal conductivity of the adsorbent bed, development of composite adsorbents etc.

Wang et al. [14] in Shanghai Jiao Tong University are working on consolidated adsorbents for adsorption refrigeration using solar energy as well as hybrid systems. Saha et al [15] in Kyushu University have done extensive research on silica gel based adsorption refrigeration using very low grade waste heat. Riffel et al. [16] have done transient modelling of an adsorber using finned-tube heat exchanger. Current research is concentrated on improving mass and heat transfer characteristics of the adsorbents and also use of advanced cycles to improve COP and SCP of the systems.

4. ADSORPTION REFRIGERATION PILOT UNIT

The 3 TR chiller unit developed is a two bed adsorption system; it uses silica gel–water pair and produces quasi-continuous cooling. It comprises of the following major sub-systems.

4.1 Solar Thermal Energy Collector Unit

The two thousand litres per day solar collector unit, installed on the roof of a two-storied building at CSIR–CMERI, Durgapur, consists of an array of solar panels along with a hot water tank and circulating pump. The solar panels have triple coated evacuated tube collectors with copper heat pipes. Table 1 lists the specifications of the solar water heating system. Figure 3 shows the schematic diagram of the solar water heating unit.

Table 1: Specifications of the solar water heating system

1. Evacuated tube collector with heat pipe	
Size	Φ47 mm x 1500 mm
Material	7740 grade, 3.3 borosilicate glass Electrolytic grade copper for heat pipes
Selective absorptive coating	Triple coated
Absorptance	0.93~0.96
Emittance	0.04~0.07
Vacuum	Absolute pressure $\leq 5 \times 10^{-3}$ Pa
Transmittance of outer tube	0.91
Stagnation temperature	~250 °C
Heat-loss coefficient	≤ 0.6 Wm^{-2}
Hailstone impact resistance	Diameter Φ25 mm
Vacuum protection	Barium getter
2. Hot water storage tank	
Tank design	Cylindrical
Inner tank material	MS tank having 8 mm thickness
Outer cladding	Aluminium alloy
Thermal insulation	Rock wool – 100 mm
Anti corrosive	Sacrificial anode – magnesium

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Fig. 3. Schematic diagram of solar water heating system

4.2 Adsorption Chiller Unit

The adsorption chiller, illustrated in figure 4, uses the adsorbent-adsorbate pair of silica gel and water. Silica gel, a well known water adsorber, is used for dehydration purposes in different domestic and industrial applications. Micro-pored silica gel, which has larger adsorption capacity at low humidity, is suitable to be utilized in a closed cycle at sub atmospheric pressure refrigeration system. Compared with other adsorbents, silica gel can be regenerated at a relatively low temperature, below 100 °C and typically about 85 °C, making it an ideal choice for solar-powered adsorption system. Water has large latent heat of vaporization and it is suitable for air-conditioning applications, because chilled water temperature required is in the range of 8–12 °C.

Table 2 shows the properties of silica gel used.

Table 2: Silica Gel Properties

Composition	SiO_2 (Minimum 98% by weight)
Bulk density	0.65 – 0.80 g/ml
Adsorption capacity @ 25° C	
40% RH	18 – 19 wt. %
60% RH	23 – 30 wt. %
80% RH	36 – 38 wt. %
Surface area	610 m^2/g
Pore volume	0.332 cc/g

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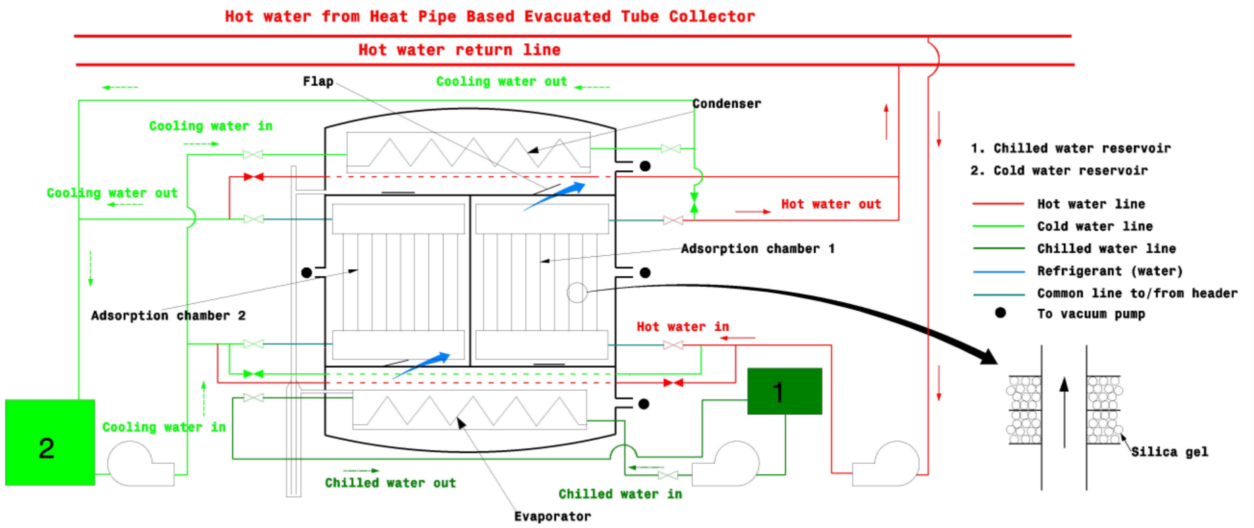

Fig. 4. Schematic diagram of adsorption chiller unit

The adsorption system has two silica gel adsorption chambers. Each chamber has a number of aluminium pipes with integral cylindrical fins to improve the heat transfer between the water flowing through the pipes and silica gel beads placed in between the fins. The condenser unit has finned copper pipes through which ambient cooling water flows. Vapour from the desorption chamber coming into condenser releases heat to the cooling water and the condensate is collected on a mirror-polish stainless steel surface. The evaporator has multiple copper trays placed one below another. Water from condenser comes to evaporator through a water seal, which maintains the pressure difference between the evaporator and condenser unit. The trays are incorporated with a hollow rectangular cross section body at their bottom surface through which pipelines of small cross section pass and water from these pipes are sprayed through the nozzle in form of fine jets at the back of tray. This facilitates evaporation of refrigerant water producing the cooling effect.

4.3 Auxiliaries

Besides these, a vacuum pump is used to set all the chambers at a low pressure initially and pressure inside them readjusts as the cycle proceeds. Vacuum pump is needed to run periodically once the cycle starts. There are three circulating pumps one each for cooling water, chilled water and hot water circuit. Low differential pressure operated flapper valves have been used to allow water vapour to travel from evaporator to adsorber and from desorber to condenser.

5. SOLAR COLLECTOR DATA

Solar collector system, installed at Durgapur, India (23.48 °N, 87.32 °E) was operated round the year. Figure 5 represents seasonal and typical daily variations of hot water temperature.

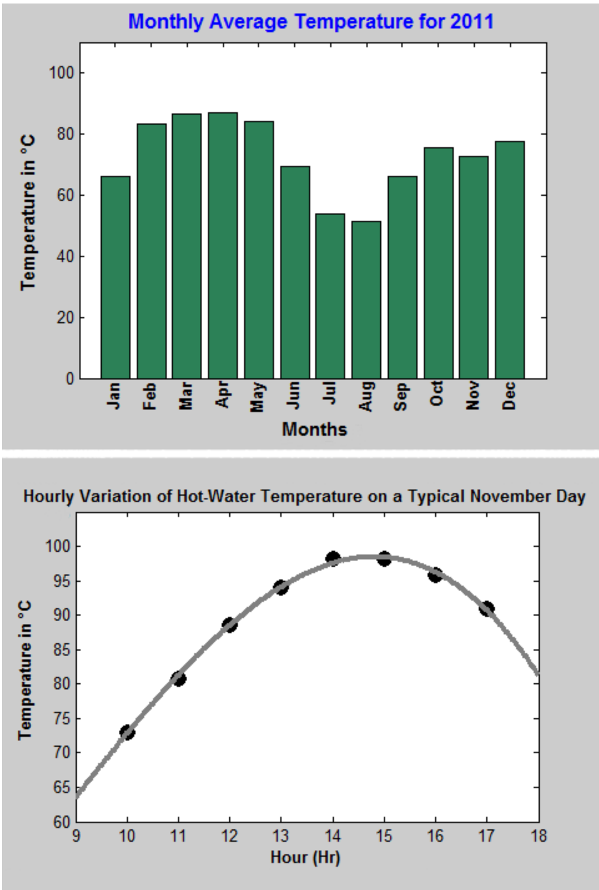

Fig. 5. Hot Water Temperature

6. SILICA-GEL BED TEMPERATURE PROFILE

The temperature profile of the silica gel bed of the above set up has been developed with the following assumptions:–

- Radial symmetry
- Heat transfer other than conductive is neglected.

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- The pipes are exposed to same conditions irrespective of their location during desorption.
- For the specific heats of metals inside the heat exchangers and the specific heats of the adsorbent and adsorbate, average values are adopted throughout the entire temperature range.

Finite difference formulations on MATLAB platform led to results depicted in figure 6.

Values adopted for simulation are as follows:

- Hot water temperature: 85 °C
- Pipe inner/outer diameter: 16/18 mm
- Circular fin diameter/spacing: 40/4 mm
- Silica gel bed annular width/height: 11/4 mm
- Silica gel bulk thermal diffusivity: 2.42 x 10^{-7} m^2s^{-1}

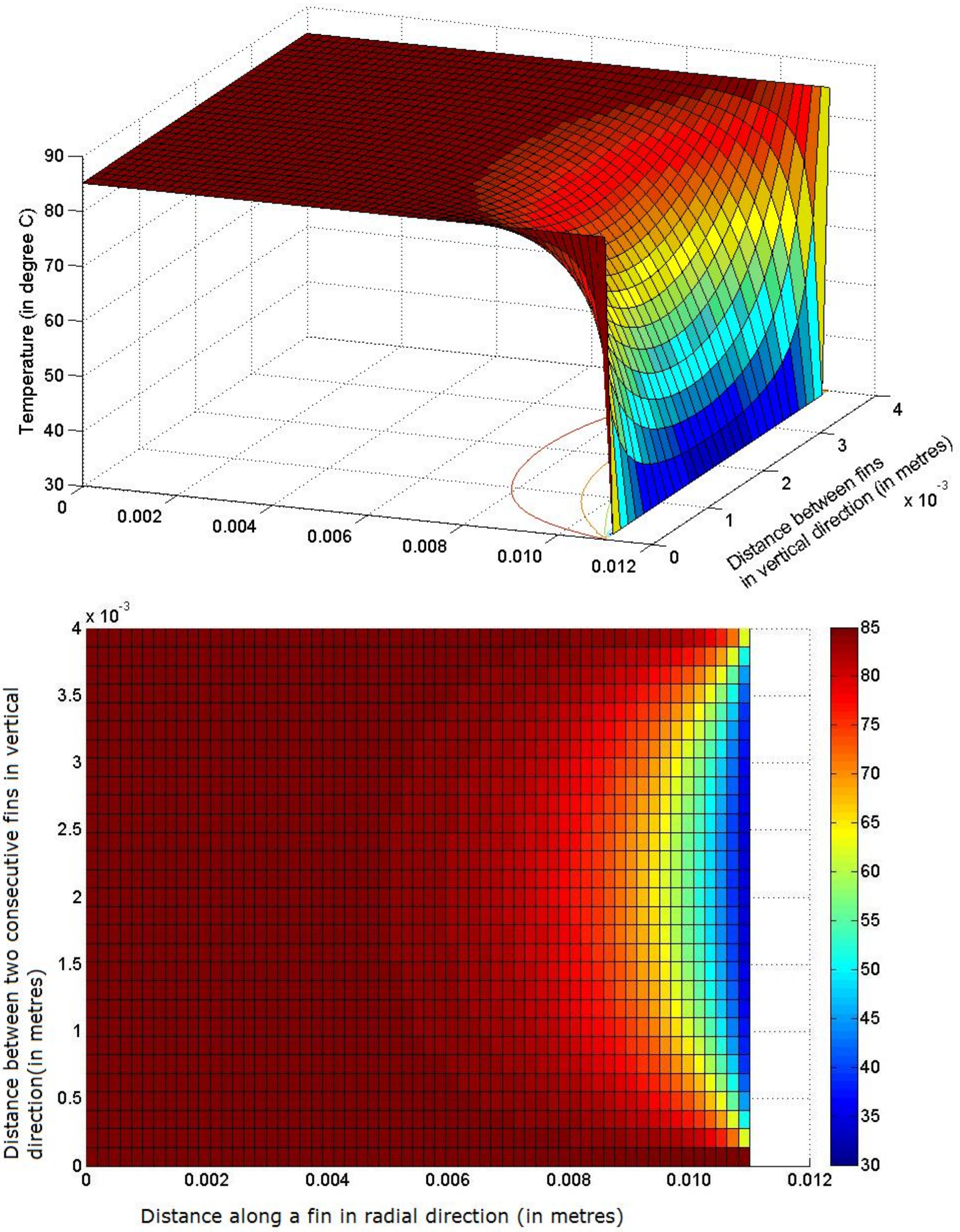

Fig. 6. Steady state temperature profile of the silica gel bed

7. CONCLUSION

Although the technical feasibility of solar-powered vapour adsorption based refrigeration is well-established, the present systems are still bulky and costly in comparison to vapour compression systems due to low specific cooling power of the adsorption chillers, which is caused, partly by the intermittent nature of operation and also by the poor heat and mass transfer properties of the existing solid adsorbents. It is clear that these systems offer environmentally clean alternative technology.

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However, since the system performance in terms of initial and running costs plays a major role for the end-user, it is essential to make these systems economically viable. Performance simulation of the adsorption chiller developed is under way, which will help in optimizing the system.

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NOMENCLATURE

Symbol

P	Pressure	(Pa)
T	Temperature	(K)
COP	Coefficient of Performance	(–)
CFC	Chloro-fluoro-carbon	
HCFC	Hydro-chloro-fluoro-carbon	
HFC	Hydro-fluoro-carbon	
TR	Tons of Refrigeration	

Subscripts

eva	Evaporation
con	Condensation

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Biplab Choudhury is a Principal Scientist in Thermal Engineering division of CSIR-Central Mechanical Engineering Research Institute, Durgapur, India. He has 14 years of research experience in the field of thermal and fluid engineering, solar thermal applications like solar cooling, drying, etc. He has also worked in coal based thermal power plants of National Thermal Power Corporation for 10 years. He has several publications in SCI journals and international conference proceedings.