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REVIEW PAPER

Solar air heater for residential space heating

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Abstract Space heating appliances require significant amount of primary as well as secondary energy. In most of the countries, energy requirements for such utilities are met by burning fossil fuel or from conventional electricity. Such usual practices for space heating result in significant increase in greenhouse gas emission and fossil fuel depletion. In the line of global emphasis on energy conservation and switch-to-clean energy approach, solar thermal energy can be harnessed using solar air heater for space heating purpose. This paper studies the potential of using solar air heater in space heating applications. Associated critical issues like demand–supply mismatch, installation space constraint, annual utilization factor and undesirable variations in output temperature are highlighted. Further, current research trends toward improving applicability of solar air heater are also briefly discussed.

Keywords Space heating · Solar air heater · Solar thermal application · Domestic heating · Solar air heater application

1 Introduction

Population growth and improved lifestyle along with subsequent technological development have led to growing demand for energy. In order to fulfill such energy demands, continuous increase in exploitation as well as consumption of conventional energy sources is observed. Consequently, (a) fossil fuel depletion and (b) rising trend in green house gas emission have become major concerns around the world. Therefore, exploitation of alternative resources has been globally emphasized in this context. Use of eco-friendly renewable energy sources for supplementing energy requirement can address issues like global warming, fossil fuel depletion and energy security.

World's building sector, comprising of residential and commercial, is one of the significant consumer of energy. According to International Energy Outlook (2016), residential sector consumes 20% of global energy consumption along with commercial building end users (International Energy Outlook 2016). Consequently, significant GHG emission from building energy consumption derived from primary or secondary energy sources is also obvious. Thus, this sector is one of the potential sectors for applying energy conservation measures and CO_2 emission reduction.

Building energy consumption includes energy consumption for heating, cooling and lighting. A large share of energy consumption is due to thermal applications. Residential thermal applications, viz., cooking, space and water heating, can play significant role in reducing building energy consumption as well as GHG emission.

Among different thermal applications in residential sector, space heating helps building comfortable environment for the occupants. Both productivity and satisfaction of building occupants are affected by thermal comfort inside the building (Ismail et al. 2010). A number of environmental parameters including air temperature and humidity and personal factors like physical activity and clothing are considered for defining thermal comfort of occupants (Djongyang et al. 2010; Wafi et al. 2011). Ambient temperature being one such factor, its control (by

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heating or cooling) is necessary to maintain satisfactory environment for building occupants. Therefore, space heating facilitates building thermal comfort and can result in increased productivity.

Residential space heating consumes a major portion of domestic energy consumption in most of the countries. Residential space heating or cooling energy requirement depends on spatial and temporal variations and hence share of heating and/or cooling in building energy consumption varies widely, e.g., 18–73% (Urge-Vorsatz et al. 2015). Urge-Vorsatz et al. (2015) reviewed trends of building heating and cooling load from 1980 to 2010 based on available data along with projection from 2010 to 2050 and observed that global residential space heating energy is 32% in 2010 with 2% in cooling out of the final residential building energy consumption (Urge-Vorsatz et al. 2015).

The spatial or temporal variations of energy consumption in residential space heating are basically dependent on number of degree days per year. Degree day is the difference between the human comfort temperature and the mean temperature on a particular day at a particular location. Thus, more number of positive degree days (heating degree days) indicate more heating energy requirement. The variations of heating degree days are influenced by regional meteorological or geographic conditions, e.g., latitude and altitude (Castaneda and Claus 2013).

Observations of residential space heating energy consumptions in different countries over the last few years indicate that such consumptions usually demand a huge share of total domestic energy consumption even though wide variations exist from northern to southern hemisphere. Typically, cold courtiers (having longer winter seasons) consume more energy for space heating. For example, in Canada, 63% of residential energy is used in space heating in 2013 (Energy Efficiency Trends in Canada 1990–2013). Further, residential sector consumes 17% of all energy use in 2013 causing 14% GHG emission and 83% of residential energy is used in space and water heating requirement (Energy Efficiency Trends in Canada 1990–2013). It is also reported that, water heating consumes 19%, while the space cooling consumes only 1% (Energy Efficiency Trends in Canada 1990–2013).

Similarly, in UK [provisional mean temperature of 9.3 °C in 2016, (Annual 2016)], more energy consumption in building heating is observed. Alfarra et al. (2013) reported that 61% of domestic energy consumption is used in space heating in UK. According to The Energy Consumption of UK (2016), Department for business, energy and industrial strategy report, domestic sector consumes 29% of final energy consumption in 2015 with an increase of 3.6% over previous year due to the heating loads (Energy Consumption In The UK November 2016). Space and water heating energy consumption is reported as high as 80% of final energy.

In China, which alone shares around 16% of worlds building energy use, residential sector consumes 85% of total building energy consumption in 2012 and water and space heating comprises a share of 52% of total building final energy use (Building Energy Use in China 2017). It is also reported that China consumes 32% of residential energy in space heating (Building Energy Use in China 2017). Also in Jordan, where temperature varies from 5 to 35 °C (http://www.weatheronline.co.uk/reports/climate/Jordan.htm.), space heating accounts for a major share in residential energy consumption. Jaber et al. reported that, in 2004, 22% of final energy consumption is used in residential sector and around 61% of residential energy consumption is used in space heating (Jaber et al. 2008). With increasing figures in population and dwellings/building space heating energy requirements are expected to rise in coming years.

Even some countries having different climatic zones demonstrate significant space heating energy consumption throughout the year. For example, Australia having seven climatic zones ranging from high humid and warm summer to cool temperate weather consumed around 41% of total domestic energy consumption in 2011 (Energy Consumption In The UK November 2016; Whaley et al. 2014). According to Australian Energy Update (2016), residential energy consumption is around 8% of total energy consumption in 2015 which is higher than commercial sector (Australian Energy Update 2016).

Consequently, residential sector significantly contributes to global CO_2 emission. According to IEA (2015), 6% of worlds CO_2 is resulted from residential sector in 2013 (CO_2 Emissions from Fuel Combustion 2015). Space heating, a major component of residential energy consumption, is commonly achieved by burning fossil fuel or from conventional electricity. In spite of having enough potential for conventional energy saving, use of solar energy in this sector is very less. According to IEA (2014) report on Heating Without Global Warming, solar thermal energy contributes only 0.4% of the global final energy use for heat in 2011 (Eisentraut and Brown 2014).

Solar air heater (SAH) is a device which can harness solar thermal energy and transform it into useable form as hot air. SAH is an attractive option for low-temperature (< 100 °C) applications like drying (Eisentraut and Brown 2014; Tyagi et al. 2012). Residential space heating, requiring low temperature, provides enormous scope for solar air heater application.

The lower seasonal requirement of SAH for space heating in some countries or regions can be compensated by using SAH in other hot air applications. SAH can provide flexibility in using solar thermal energy. Apart from space heating, hot air can be used for several other residential applications like drying of clothes, fruits, vegetables and other agricultural or marine products, particularly in the low-temperature range. Thus, appropriate designs of solar air heater can be effective means of using solar thermal energy for need-based applications and hence can significantly contribute to saving of fossil fuels as well as reduction in green house gas emissions.

Residential space heating using solar energy can be achieved in many ways. Using solar passive architectures or building integrated systems are the most common methods. However, such methods are usually more appropriate for new constructions or otherwise extensive design data for the existing building as well as subsequent modifications are essentially required.

The present paper aims at promoting development of standard variants of modular solar air heater, which can be conveniently used for space/air heating, particularly at low temperatures (< 100 °C), and which can reduce the conventional energy usually consumed for space/air heating in residential sector. Commercialization as well as popularization of the SAH is the motivation behind this study.

The background is based on the fact that huge share of domestic energy consumption is expended for meeting the space heating energy requirement in most of the countries. Further, fossil fuels are the most common sources for fulfilling space heating energy need. On the other hand, SAH provides useful thermal energy by harvesting a renewable energy source, viz., solar energy. Besides, apart from being a renewable energy device, SAHs are featured by simple working principle or constructional simplicity as well as easy installation and hence can be effectively and extensively used for supplementing space heating energy requirements. It is expected that resolving certain issues would lead to the development of widely acceptable standard commercial variants of modular SAH. Such market can provide flexibility to users in choosing suitable SAH designs according to the need for their existing residential buildings. Consequently, a sustainable market promoting scope for need-based-SAH-selection would be developed which can play a key role in popularizing SAH use in residential applications. Thus, the extensive use of solar air heater is expected to increase the share of renewable energy in the global energy mix, reduce carbon emission from fossil fuel combustion for air/space heating as well as facilitate saving of natural resources.

2 Space heating systems using solar energy

A solar energy-based heating system is mainly categorized by the working fluid used in the collector. The working fluid can be either air or liquid (water, antifreeze solutions like non-toxic propylene glycol, etc.). Although their general constructional features vary in some aspects due to differences in thermo-physical properties of the fluids, their basic working principles remain the same. The fluid, which moves from inlet to outlet, carries the thermal energy absorbed by the collector. The heated fluid is then collected from the outlet for desired applications directly or for storing in a tank (most common with liquid). Movement of the fluids can be achieved by either natural convection or forced convection. In natural convection, density difference of the hot and cold fluid is used to move the fluid up (thermosiphon), while in the forced convection, fans or blowers are used for maintaining the fluid flow from inlet to outlet. Both of these types can be used for space heating purposes in two modes, viz., active and passive (https://energy.gov/energysaver/active-solar-heating). Unlike passive systems, active systems use mechanical and electrical devices such as fans and blowers, for enhancing the process of heat capturing from the solar radiation and delivery to the utility point. Hence, active systems are more effective and most commonly used for space heating as they provide added flexibility of using harvested solar thermal energy in different utility points as per requirement.

Commercial liquid-based (home) space heating systems can be with or without separate heat exchanger and usually have storage tanks. Liquid-based systems are more suitable for centralized heating. Space heating is achieved by radiant system or forced air system (https://energy.gov/energysaver/active-solar-heating). In the radiant systems, hot liquid flows through tubes embedded in floor, wall or ceiling. The thermal mass of the building materials retains the heat from the hot liquid and maintains the room temperatures during night times. In case of forced air system, a liquid to air heat exchanger is used and the cold air from the living space is passed through the heat exchanger (Kerme and Kaneesamkandi 2015). The hot air from the heat exchanger is then fed back to the living space by using blower or fans.

The passive air-based space heating systems depend on building features like orientation toward sun as well as building structure or shape and materials. In fact, these are often become part of building design rather than installation in an existing building. On the other hand, the active systems can be installed in an existing building with some modification to facilitate ducting of air. They can use glazed or unglazed collector and the heated air is directed through appropriate ducting to the living space by means of fans or blowers. Since the hot air generation depends on the solar radiation, these systems require heat storage materials or devices for hot air delivery during night time.

Also, according to the type of installation and basic functional features, solar energy-based space heating systems can be categorized into (a) standalone or independent system, (b) combi-system and (c) district heating system (Faninger 2010; http://solar-district-heating.eu/; Clean Energy Project Analysis 2005). Modular solar air heaters meant for heating of a specific area can be grouped in standalone systems. Various design configurations like change in glazing, air flow pattern, etc., are used in such systems. Tyagi et al. reviewed on different designs of solar air heater with and without heat storage provisions (Tyagi et al. 2012). Exploring use of existing building features for air flow management can result in more benefit from such systems.

A combi-system is featured by multifunctional ability. It provides heat for more than one purpose in the installed location, space and water heating being the most common applications. Combi-systems for water and space heating are more common in central Europe, particularly in Germany, Austria, Switzerland and France and are reported to replace 20–30% of overall energy requirement for water and space heating (Faninger 2010). Solar-assisted heating and cooling (SHC) systems can also be included in combi-systems. Besides water and space heating, SHCs also encompass designs for cooling and industrial process heating (Faninger 2010). Combi-systems can provide more benefit in locations having lower annual space heating requirement.

The district heating systems use heat nets which connect different locations or buildings requiring thermal energy (http://solar-district-heating.eu/; Linking Heat and Electricity 2014; Solar Heating and Cooling Application Factsheet 2015). Small heat nets connect few buildings or villages, while larger ones connect bigger cites. Thermal energy from solar collectors is supplied to desired locations through these nets. Such systems can be centralized or distributed type. In centralized systems, solar collectors deliver heat to a central store for distribution to different locations. The heat storage systems can be (a) seasonal or (b) diurnal type (http://solar-district-heating.eu/; Solar Heating and Cooling Application Factsheet 2015; Quintana and Kummert 2015). Seasonal storage systems store heat during summer for using in winter, whereas diurnal storages are meant for day–night operation. In the distributed types, solar collectors are installed in different locations and are connected to the primary heating network of the site. Temperature or heat flow control mechanisms are very important in such systems. Quintana and Kummert (2015) investigated the role of control strategies on the overall performance of a district heating plant. Controlling different system components according to varying energy requirement is important for better performance in such plants. Larger seasonal storage and optimum control strategy can reduce annual demand of conventional energy for space heating.

According to heating and cooling program reports of International Energy Agency, global solar thermal installations show around 12% yearly increase since 2000–2011 (Solar Thermal in the Mediterranean region 2012; Mauthner and Weiss 2011). In 2012, the total installed capacity reached at 269.3 GWth (384.7 million m^2) (Mauthner and Weiss 2011). Although the overall solar thermal installations are increasing around the world, the growth of air collector is far less than the water collectors. The air collectors have been sharing only a little fraction since 2000 (Fig. 1a–c) as compared to the growth of water collectors (Solar Thermal in the Mediterranean region 2012; Mauthner and Weiss 2011; Weiss et al. 2001). This indicates that the growth of solar air heaters is not up to the mark despite having potential for supplying energy need and there are certain issues yet to be addressed appropriately.

3 Prospects of solar air heater (SAH)

Space heating energy is an important factor in residential energy consumption. The share of residential space heating energy varies from country to country depending on the climatic conditions. However, the share of conventional sources like fossil fuels for getting such energy remains almost stable for a particular region. For example, Bianco et al. reported a stable share of 82% of natural gas in residential sector for space heating in Italian context during the decade 1990–2009 (Bianco et al. 2017). Thus, SAH can have consistent opportunity for saving natural resources consumed in space heating applications.

3.1 Resource and demand

Input energy required for functioning of a solar air heater is solar energy. The most important feature favoring solar air heater application is the abundance of input energy. According to IEA (2011a), ideal potential of solar energy is about 6200 times of global primary energy supply (Eisentraut and Brown 2014). This implies that sufficient resource is available for fulfilling global space heating energy requirement. The earth receives solar radiation at a rate of approximately 1.8×10^{14} kW (Tyagi et al. 2012; Thirugnanasambandam et al. 2010; Panwar et al. 2011). However, annual solar radiation varies depending on geographic location. Typical range of solar energy available per year is 775–2500 kWh/m^2 from Lerwick, UK (60.15°N, 1.14°W) to Sahara desert, Africa (23.80°N, 11.28°E), respectively (Faninger 2010; http://www.shetland.climatemps.com). Geographic locations near equatorial Sun Belt have advantages of receiving enough solar energy. For example, India, having around 300 clear sunny days per year, is one of most prospective countries for harvesting

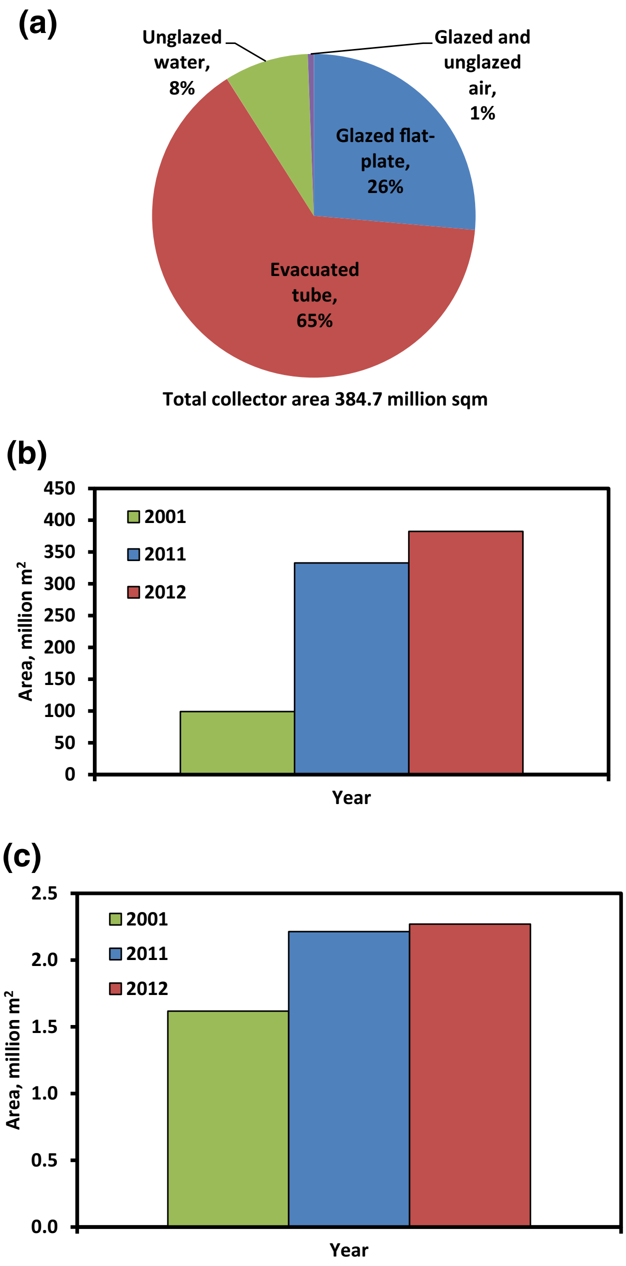


Fig. 1 **a** Sharing of collector types in 2012, **b** Growth of water collector in 2001, 2011 and 2012 and **c** Growth of air collector in 2001, 2011 and 2012 (Solar Thermal in the Mediterranean Region 2012; Mauthner and Weiss 2011; Weiss et al. 2001)

solar thermal energy (Ojha et al. 2014; Khare et al. 2013). Harvesting of available solar energy by using simple device, viz., SAH, can significantly reduce the increasing pressure on the fossil fuels across the world.

SAH has also long-term commercial prospect. According to international energy outlook, by 2040 global residential sector energy consumption will increase by 48% over 2012 at an average rate of 1.4% per year (https://www.eia.gov/outlooks/ieo/buildings.cfm). Increase in household is one of the major drivers for such increase. Urge-Vorsatz et al. projected population increase as 41%, while the floor space increases 94% in next four decades from 2010 (Urge-Vorsatz et al. 2015). Although precise data for space heating energy consumption alone are not available, similar increase in space heating energy requirement can be expected considering the population growth as well as new residential building and improved lifestyle. Such increased demand supports a stable and sustainable market for SAH.

3.2 Cost

Cost of a solar air heating system comprises of (a) capital cost and (b) operating or heat generation cost. Capital cost, which includes system cost apart from installation cost, depends on (a) design of SAH, collector in particular, e.g., evacuated, flat plate, etc., (b) availability of technical resources and (c) locational/regional influence (Solar Thermal in the Mediterranean region 2012; Karagiorgas et al. 2001). Use of different geometry or material for absorber, mode of air circulation (forced or natural convection) and heat storage facility leads to variations in SAH design and affects system cost. Besides, region-specific availability of materials and accessibility to sophisticated technology affect capital cost of a particular SAH design. However, proper consideration to spatial variations of solar radiations and local resources can result in cheaper site-specific design for same output energy.

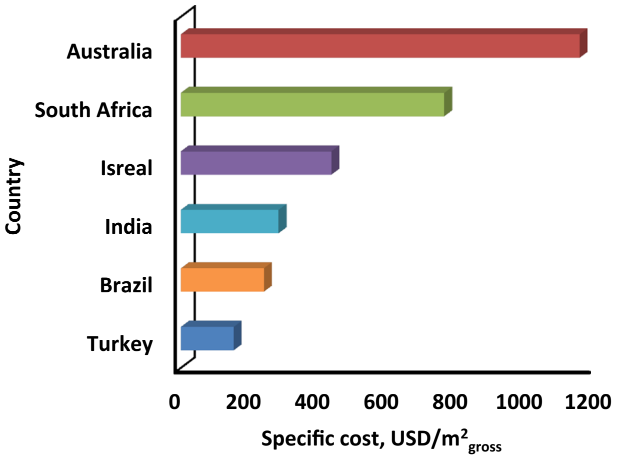
Cheaper heat generation cost is another advantage of solar air heater. Heat generated from solar thermal systems is economically attractive than from gas or electricity in most of the countries (Jaber et al. 2008; Eisentraut and Brown 2014; Solar Thermal in the Mediterranean region 2012; Karagiorgas et al. 2001). Since input energy for SAH, viz., solar radiation, is free of cost, the fuel cost for heat generation is practically nil. The overall cost of heat generation can be substantially reduced by deriving required power for subsidiary air flow management or control devices (blower, temperature controller, etc.) from solar or other renewable energy sources.

Reliable and specific data for commercial solar air heater is not available to the best of the knowledge of the authors. This is due to the fact that, a global market of solar air heater is yet to be developed. More specific studies in this area are felt to be very necessary. However, considering the similarity of working principles of solar water and air heating systems, reported cost of solar water heating systems can be considered as reference. Further, the capital cost of a solar air heater can be well expected to be lower than the water (liquid) heater for same collector area as it can be used without storage tank. They also do not require sophisticated safety and precautionary measures such as antifreezing of working fluid, leakage and corrosion problem, and hence can result in further reduction in cost of tubing or ducting.

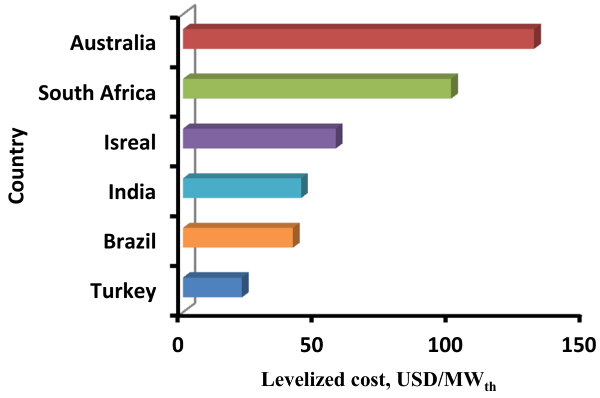
Specific cost (cost per unit of gross collector area including installation cost) and cost of heat generation (cost per unit of energy supplied) are two important parameters for studying the economics of solar thermal system. Specific cost represents capital investment including installation cost for a particular system. The cost of heat generation can be more effectively represented by levelized cost. Levelized cost takes into account of specific system cost including installation, operating and maintenance cost and system's service life (Branker et al. 2011). Appropriate discount rates are also applied for calculating the levelized cost. Both specific cost and the levelized cost vary widely from country to country.

Depending on the type, size and location, capital cost of a solar thermal system varies up to around ten times from a minimum of US$ 240 per kW_{th} across the world (Eisentraut and Brown 2014). Similar rate of variations is also observed in the cost of heat generation. According to the IEA solar heat worldwide report 2016 (Mauthner et al. 2014), specific cost of solar liquid-based heating system (water and/or space heating) varies from 150 to 1920 $US\$/m^2_{gross}$, while the levelized cost of heat calculated over the service life up to 25 years varies from 20 to 220 US$/MWh (Table 1). Typical variations of cost due to regions and system size can be seen in Figs. 2 and 3. It can be seen from Fig. 2 that small systems usually have higher costs compared to larger ones. On the other hand, cost of heat generation through electricity and natural gas-based system varies US$ 75–260 and US$ 40–100/MWh_{th}, respectively (Eisentraut and Brown 2014). The cost of heat generation for solar air heater can also be equally competitive with fossil fuel-based heating systems in a particular country due to added environmental benefits.

Martinopoulos (2014) investigated the economics of active solar heating systems (space and water) in context of achieving nearly zero energy building (NZEB) in Greece (Martinopoulos and Tsalikis 2014). The extensive economic analysis based on net present value of the investment (NPV) and discounted payback period (DPEB) demonstrated viability as well as attractiveness of such systems in supplementing thermal energy requirement. Considering costs of different systems (8–12 m^2) in the range of 2800–3500 € and annual space heating loads at four different cities as 246–3414 kWh, the DPBP was observed as low as 4.4 (oil substitution) and 8.5 (natural gas substitution) years which indicated that such systems are economically attractive in space heating applications.



(a) Specific cost

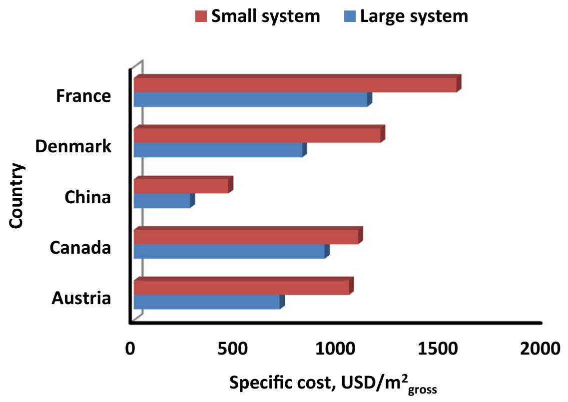


(b) Levelized cost

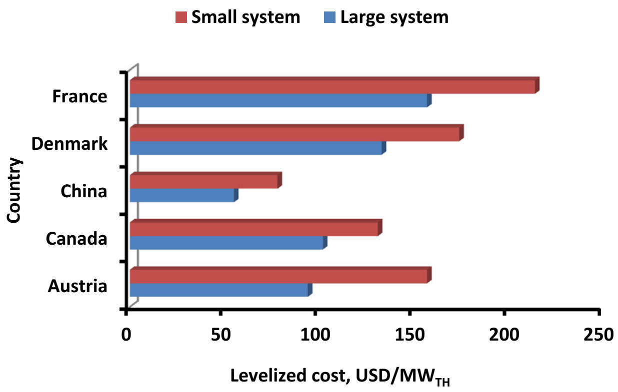
Fig. 2 **a–b** Average **a** specific and **b** levelized cost of natural convection type solar hot water system in different countries Mauthner et al. (2014)

Table 1 Variation of cost according to type of solar heating system Mauthner et al. (2014)

Domestic systems	Application	Specific cost (USD/m^2_{gross})	Levelized costs (USD/MWh_{th})
Thermosiphon/natural convection	Water heating	120–1350	20–130
Pumped/forced convection	Water heating	150–1920	20–220
Combi-system	Water and space	210–1490	30–200



(a) Specific cost



(b) Levelized cost

Fig. 3 **a–b** Average **a** specific and **b** levelized cost of small (2–4 m^2_{gross}) and large (20–75 m^2_{gross}) forced convection solar hot water system in different countries Mauthner et al. (2014)

In general, different designs of conventional space heating systems (hydronic or forced air) are available (Martinopoulos et al. 2016). Among different desirable features such as adjustable temperature and better indoor air quality, lower initial investment and operational costs are the most important parameters for selecting space heating systems from users' point of view. Solar air heaters can be potent competitors for conventional systems running on fossil fuels in these aspects. By appropriate correlation among various influential factors like locally available resources in terms of materials, technical skills and existing or traditional building structures, an effective design can be fabricated at optimum cost. Site-specific designs along with proper material selection can reduce the system cost without sacrificing much in terms of efficiency or output.

3.3 Conversion efficiency

High conversion efficiency can be cited as another advantage of solar air heater. Conversion efficiency of a solar thermal system [50–60% for typical flat plate collectors (Faninger 2010)] is usually higher than photovoltaic system [10–20% for commercial Si-cells (Mittelman et al. 2007)]. The conversion efficiency of a solar air heater depends primarily on (a) absorber design/geometry, (b) absorber material property and (c) thermal insulation (Yeht and Lin 1996; Duffie and Beckman 1991; Choudhury and Baruah 2014). Using more efficient collectors like evacuated tube or transpired collectors can lead to increase in useful thermal energy gain from a solar air heating system.

Variations in efficiency with respect to designs are reported by many researchers. Absorber material properties (e.g., absorptance, transmittance) and geometries (Kumar et al. 2015; Pakdaman et al. 2011; Chabane et al. 2014), number of transparent covers (glazing) (Belusko et al. 2004) and geometry of air passage (Budea 2014; Forson et al. 2003) greatly influence the outlet temperature in a solar air heater. Considering variations in design and location, usually 300–900 kWh of thermal energy per year can be extracted by a collector of 1 m^2 surface area (Faninger 2010). Flat plate SAH, being a simple design with good conversion efficiency, can play important role in complementing residential energy demand for hot air applications.

Figure 4 shows typical performance of some commercial solar air heaters used for building/space heating. The variations of maximum instantaneous efficiencies among different types are in the range of 80–90% and resulted from design variations, viz., material, air flow or absorber geometry (Enerconcept; Matrixairheating; Grammer-solar;

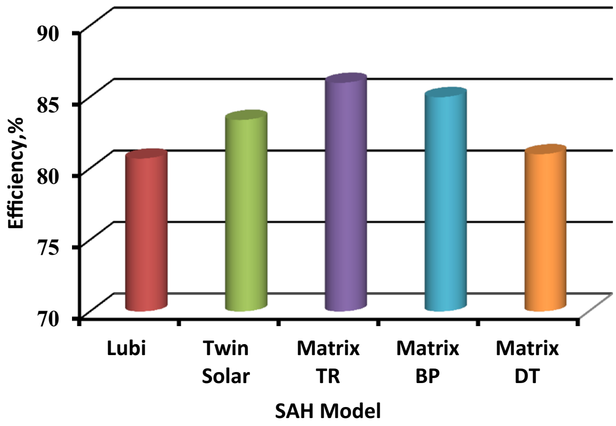


Fig. 4 Maximum instantaneous efficiency of some commercial solar air heaters (Enerconcept; Matrixairheating; Grammer-solar; Solardirect)

Solardirect). Table 2 shows the general specifications of the collectors and their mounting options. Based on the model or designs, these air heaters can be mounted on the facade, wall or roof of the building. Average operating efficiencies of these systems are reported as around 60% with the maximum power output in the range of 600–800 W/m^2 (Enerconcept; Matrixairheating; Grammer-solar; Solardirect). The corresponding temperature rise falls in a range of 17–45 °C above the ambient temperature (Enerconcept; Matrixairheating; Grammer-solar; Solardirect).

3.4 Clean environment

Above all, use of solar air heater for space heating facilitates global emphasis on clean energy approach. Combustion of fossil fuels for heat and electricity is one of the major causes for increasing GHG emissions or air pollution. Thus, use of fossil fuels for residential space heating is also a major factor in contributing increase in GHG emissions or air pollution.

According to IEA Statistics (2015), CO_2 from energy consumption represents around 60% of global GHG emission (CO_2 Emissions from Fuel Combustion 2015). The statistics also reveals that, fossil fuel combustion for heat and electricity production results in 42% of global CO_2 emission in 2013 (CO_2 Emissions from Fuel Combustion 2015) out of which residential sector is the second largest contributor with 11%, just behind the industries (18%) (CO_2 Emissions from Fuel Combustion 2015). On the global basis, residential sector contributes around 6% of global CO_2 emission (CO_2 Emissions from Fuel Combustion 2015). Region or country wise, this figure can be much higher, e.g., 14.4% of total CO_2 emission in Argentina (Gonzalez et al. 2014). Similarly, in EU, residential space heating shares as high as 69% (2013) of the total household energy consumptions resulting in 9.9% of total CO_2 emission (Martinopoulos et al. 2016). Since fossil fuel and conventional electricity are traditional sources for meeting thermal energy need in most of the countries, use of solar energy in this aspect can certainly cause significant reduction in global GHG emission.

IEA identifies building sector as one major sector for GHG emission reduction which can serve the purpose through application of cost effective measures (Bridge Strategy) (Energy and Climate Change 2015). The Paris Agreement (COP 21) results in formulation of mechanisms for promoting mitigation of greenhouse gas emissions along with sustainable development (CO_2 Emissions from Fuel Combustion 2015; http://www.cop21paris.org). Many developing countries like India have already emphasized on solar energy use in this line (India Solar Handbook and Bridge To India 2014). Growing thrust in international cooperation treaties or policies for sharing financial and technological support in renewable energy exploitation can be a good backup for solar air heating systems.

The reported annual energy gain from all water-based thermal systems in 2014 is equivalent to about 36.1 Mtoe which corresponds to about 116.4 million tons of CO_2 emission reduction (Mauthner et al. 2014). Figure 5a–b shows the contribution of different types of water-based systems toward energy saving as well as CO_2 emission reduction. The major share of such significant saving in CO_2 emission came from the small-sized (single family) domestic hot water system (68%). Such figures also reflect the huge marketability of small-sized solar air heating system in residential sector. Innovative modular designs supported by region-specific economics can lead to extensive use of SAH in residential space heating as well as other hot air applications, and hence more reduction in CO_2 emission can be achieved.

Table 2 General specification and mounting options for some commercial solar air heaters (Enerconcept; Matrixairheating; Grammer-solar; Solardirect)

SAH model/type	Manufacturer	General specification	Integration/mounting
Lubi	Enerconcept Technologies, Canada	Perforated poly carbonate transparent collector, smaller (0.3 sqm) modules available	Existing ventilation system, wall or roof
Twin solar	Grammer Solar Germany	Ripped absorber, ventilator and PV module integrated, 2–6 m^2 modules	Ventilation system
Matrix TR	Matrix Energy Inc, Canada	Unglazed transpired exterior metal cladding collector, sized according to air requirement of the building/space	New constructions, retrofits, wall
Matrix BP	Matrix Energy Inc, Canada	Active back-pass collector, 0.3-m-wide exterior metal cladding	New construction, upper wall
Matrix DT	Matrix Energy Inc, Canada	Delta type, flat transpired absorber with built in air plenum, integrated solar collector and air duct	Roof

4 Critical issues

The major issues hindering growth of solar air heater installations are briefly highlighted below.

4.1 Asynchronous demand and supply

SAH transforms solar thermal energy into sensible heat only when radiation is available and cannot provide desired output during no sunshine (e.g., night time) or low radiation periods (Pinel et al. 2011). Asynchronous demand and supply is one of the important issues for limited growth of SAH.

Hot air supply from a particular SAH design depends on operating flow conditions (mass flow rate in particular) and solar radiation (Thirugnanasambandam et al. 2010; Karim and Hawlader 2004; Tiris et al. 1995). Solar radiation is the most dominant among these variables. Thermal energy output from SAH is governed by available sunshine hours as well as level of solar insolation. More sunshine hours and higher insolation level result in more thermal energy output from SAH. However, the hot air requirement is not fully dependent on these factors. There should be adequate provision for meeting thermal energy need during low or no radiation periods.

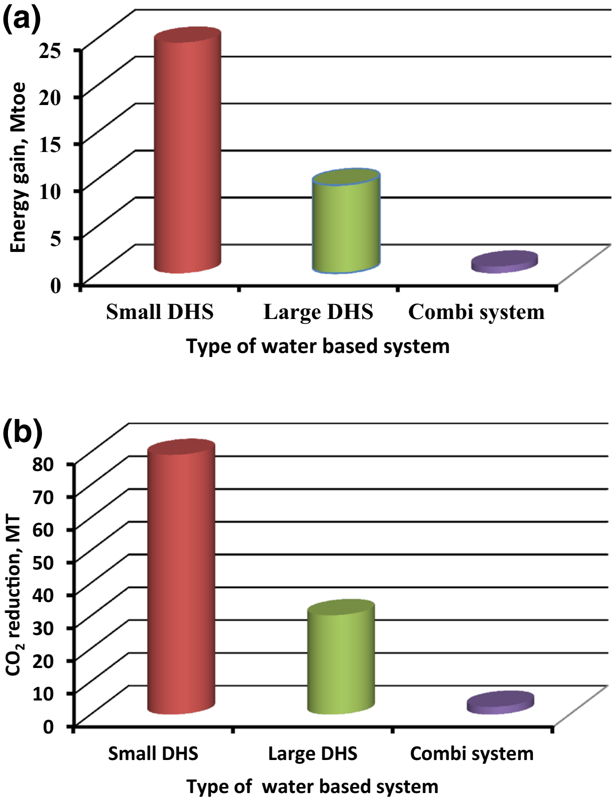


Fig. 5 **a** Energy gain from all water-based solar thermal system in 2014 and **b** CO_2 reduction from all water-based solar thermal system in 2014 Mauthner et al. (2014)

Sunshine hours and insolation level vary with season and latitude. Prolonged cold season affects annual thermal energy yield from a SAH due to reduced periods of sufficient solar radiation. Typically, geographic locations with higher latitude receive solar radiation at a much higher rate (more than twice) during summer than winter (Faninger 2010). On the other hand, the space heating requirement becomes apparently much lower than cooling requirement during these periods. An ideal SAH should provide required hot air irrespective of seasonal interval or geographic location.

Getting desired output from SAH during low or no sunshine periods requires additional arrangements of appropriate facilities. There are basically two strategies for addressing this issue; (a) using SAH in hybrid mode and (b) using heat storage materials with SAH. In hybrid mode, other heating devices using conventional energy sources can be coupled to the output of the SAH. Such auxiliary devices can be used for compensating the shortfall of thermal energy during unfavorable periods. However, automatic switching of operating mode from SAH to auxiliary heating device is more preferable than manual operation which requires dedicated manpower.

Figures 6 and 7 demonstrate the use of SAH in these modes. As in Fig. 6, when space heating energy (Q_D) is not required, or the amount of energy available from SAH (Q_S) is more than required space heating energy (Q_D), the output of SAH, viz., ($Q_S - Q_D$), can be diverted to some heat storage device. Such heat store can supply the shortfall of energy ($Q_D - Q_S$) during periods of insufficient SAH output such as nights or low radiation periods. The backup time for supplementing desired space heating energy will depend upon the capacity of the heat storage device. Designing modular heat storage devices with different levels of capacity will provide more flexibility to customers in choosing suitable backup according to need and budget.

Figure 7 shows the integration of SAH with auxiliary air heating device. During periods of no or insufficient SAH output, auxiliary air heating device can supply required space heating energy ($Q_D - Q_S$). On the other hand, appropriate energy regulator or baffles can be used to get desired energy from SAH during high output conditions. In

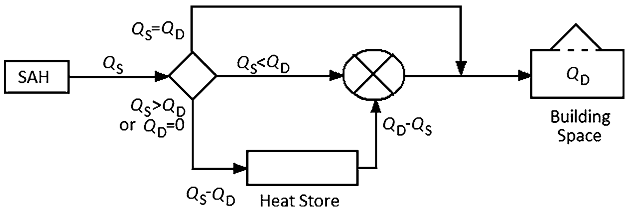


Fig. 6 Block diagram of integration of SAH with heat storage device

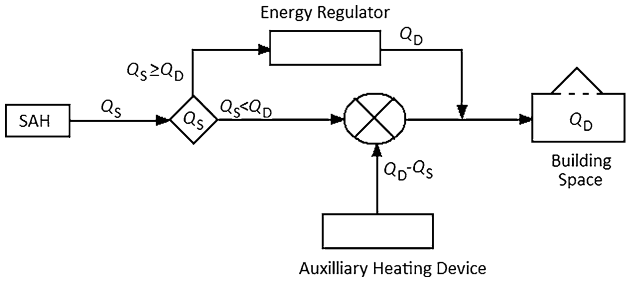


Fig. 7 Block diagram of integration of SAH with auxiliary air heating device

such situations, SAH designs should have adaptability to facilitate integration with standard electrical or other air heating devices as well as energy regulators.

Enhancing SAH effectiveness by using heat storage materials is favorable strategy in current research as it reduces the need of auxiliary air heating systems. Heat storage facilities enhance effectiveness of SAH by facilitating output during no sunshine periods and smoothening temperature variations at the output (Saravanakumar et al. 2012; Tiwari 2002). Such facilities allow storing thermal energy during sunshine hours which can be used during no sunshine period.

Effectiveness of various heat storage techniques have been investigated many researchers. Pinel et al. (2011) and Dincer and Dost (1996) review various heat storage techniques as well as storage media. Bal et al. (2011) also review the thermal heat storage systems with respect to drying applications. Figure 8 shows basic classification of different types of solar thermal energy storage methods (Pinel et al. 2011; Tiwari 2002; Dincer and Dost 1996; Bal et al. 2011).

Among different methods, use of phase change materials (PCM) is becoming increasingly popular for heat storage (Chidambaram et al. 2011; Zalba et al. 2003). PCM is basically used in the principle of latent heat storage method. They can absorb or release large amount of energy at a constant temperature by changing phase of the materials, e.g., (a) solid–gas, (b) liquid–gas and (c) solid–liquid. PCM offers added features in terms of cost and aesthetics compared to earlier techniques, viz., water tanks or rock bed storage. PCM has higher thermal energy storage densities than sensible heat storage materials. Latent heat storage method using PCM can reduce size of the storage system than others for storing same amount of thermal energy.

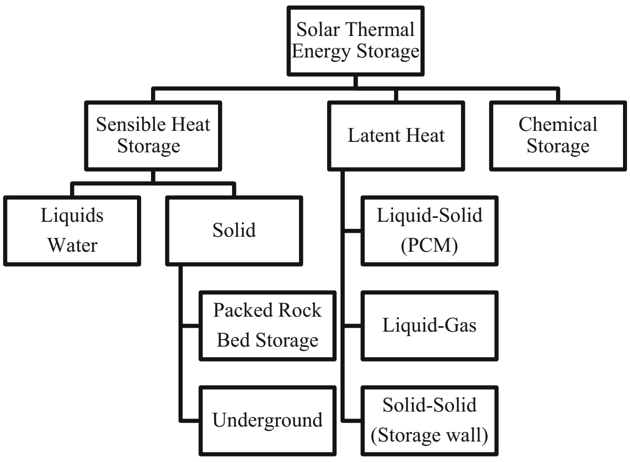


Fig. 8 Different solar thermal energy storage methods (Pinel et al. 2011; Tiwari 2002; Dincer and Dost 1996; Bal et al. 2011)

The impact of natural convection in phase changing process of PCM is affected by geometry of the system. Saman et al. (2005) investigated the impact as well as performance of a roof integrated solar space heating system for domestic application in a house in Adelaide, Australia. The system used calcium chloride hexahydrate as phase change materials for heat storage. In absence of sunshine, the stored heat is facilitated to the living space. For effective heat transfer through natural convection appropriate geometry with respect to the PCM and the building should be used.

4.2 Installation space and building aesthetics

Available space for SAH installation along with maintaining existing building aesthetics is another important factor affecting growth of SAH.

Lack of appropriate mounting space in a building can restrict installation of SAH of required capacity. Capacity of SAH usually is specified by collector area and determines possible energy output for a particular location. Installation of SAH essentially requires appropriate space for mounting the collector of required size. Suitable installation space is characterized by (a) availability with respect to required capacity, (b) proper orientation for collecting optimum solar radiation and (c) causing minimum loss of building aesthetics.

Required capacity or sizing of SAH for space heating depends on (a) thermal energy requirement, (b) average daily solar radiation at a particular location and (c) thermal conversion efficiency of the particular design. Thermal conversion efficiency is an important parameter which affects sizing of SAH. SAH demonstrates poor thermal efficiency compared to solar water heater because of poor heat transfer between air flow and absorber, and hence system size is increased for same output energy (Duffie and Beckman1991; Belusko et al. 2004; Boulemtafes-Boukadom and Bonzaoui 2014). SAH designs with higher conversion efficiency can reduce the size of SAH for same energy requirement which in turn can reduce space requirement. However, such designs should be commercially attractive from users' point of view.

SAH conversion efficiency can be enhanced by manipulating design parameters like absorber geometry, material and air flow passage. Various designs of collector have been developed by researchers and tested for change in efficiency (Yeht and Lin 1996; Pakdaman et al. 2011; Chabane et al. 2014). Major design approaches include selection of absorber material with different heat transfer property, different geometry of absorber as well as different patterns for facilitating airflow. Other approaches are changing number of glazing, type of insulations and incorporation of artificial roughness.

Use of absorber materials having better heat transfer properties increases conversion efficiency. However, this may also raise the overall system cost. Manipulation of absorber geometry can be a good choice for the purpose. Changing the geometry of the absorber affects the turbulence of air flow and subsequently the sensible heat output. Artificial roughness plays an important role in this aspect.

Artificial roughness in absorber is the incorporation of various shapes or sizes in different arrangements or orientations (Boulemtafes-Boukadom and Bonzaoui 2014; Bekele et al. 2014; Varun 2007; Saini and Verma 2008). They can be classified into (a) transverse fixed roughness in continuous or discrete distribution and (b) traditionally produced through machining, casting, welding, etc. Adversely, artificial roughness introduces friction losses. Appropriate optimization between degree of roughness and developed friction losses is essential for overall increase in efficiency. Computational fluid dynamics (CFD)-based numerical analysis demonstrates scope of heat transfer enhancement through artificial roughness in absorber without significant adverse effect of friction loss (Boulemtafes-Boukadom and Bonzaoui 2014). By applying optimum artificial roughness efficiency of an existing SAH can be significantly improved.

Forson et al. (2003), Romdhane (2007) and Chabane et al. (2013) investigated effect of changing air flow configuration or air mass flow rate on collector efficiency. Higher mass flow rate apparently increases collector efficiency, but it also reduces output temperature by impairing absorber-to-air heat transfer. Optimum flow condition needs to be identified for best operating efficiency of SAH with minimum reduction in output temperature.

SAH output prediction model can be helpful in this context. Gonzalez et al. (Gonzalez et al. 2014) determined optimum air flow rate for fast heating of indoor spaces under specified operating conditions with a prototype fabricated at Instituto de, Investigaciones en Energía No Convencional, Universidad Nacional de Salta (INENCO), Argentina. A model was developed for predicting thermal behavior of counter-flow double-pass solar air heater. Experimental results justified model's applicability in estimating outlet air temperature under different operating conditions like outdoor temperature and solar radiation. A collector specific performance prediction model can help in taking corrective measures during the periods of low or insufficient thermal energy output from the SAH.

Use of baffles in the air flow passage is also a potential technique for efficiency enhancement. Better fluid mixing, and hence better heat transfer, can be accomplished by incorporating vortex generators such as ribs and baffles (Boulemtafes-Boukadom and Bonzaoui 2014; Visagavel and Srinivasan 2010). Budea (2014) experimentally investigated changes in conversion efficiency of commercial solar collectors against various parameters including air flow rate under the climatic condition of Romania, Southeastern Europe. Use of baffles and double air passage can raise collector efficiency over 50% under 900–1000 W/m^2 solar radiation, which is much higher than maximum efficiency (38%) of a galvanized iron and single pass collector (Budea 2014). A computational model for living space ventilation is beneficial to find out the best strategy for optimal working of collectors.

Among different designs of collectors, evacuated type and transpired solar collectors (TSC) are very effective in conversion efficiency improvement. Evacuated solar collector improves overall system performance. The TSC is a combination of perforated solar absorber sheet, ducting and fan (Alfarra et al. 2013) which is used to preheat the ambient air and then the hot air is drawn into the building for space heating. Low capital cost along with higher instantaneous efficiency, e.g., more than 70% (Alfarra et al. 2013; Zhai and Wang 2008), makes TSC as a potential technology for thermal applications. Such designs with improved efficiency can compensate for limited space available for SAH installation.

Proper consideration to building aesthetics is also important along with enhancement of conversion efficiency. Large-sized systems and/or inconvenient designs often destroy the building aesthetics which adversely affects interests of prospective consumers. Modular and portable SAH designs can meet varying thermal energy requirement of different consumers, enhance installation flexibility and reduce damage to building aesthetics.

Using existing building structures is also a good choice for preserving building aesthetics. Several researchers report effect of using existing building features, e.g., roofs, building walls, etc., on overall performance (Belusko et al. 2004; Saman et al. 2005; Zhai and Wang 2008; Medved et al. 2003). Saman et al. (2005) investigated roof integrated solar heating system with heat storage facilities (PCM). The authors studied the effect of natural convection on the performance of heat storage through PCM. Belusko et al. (2004) also reported improvement of efficiency of a roof integrated system for space heating with appropriate glazing and heat storage unit. Investigations along with economic analysis reveals cost effectiveness compared to conventional systems in Australia. Using building features with suitable number of glazing can improve efficiency of solar air heater at lesser cost. Exploring scope of using existing roof construction as the solar thermal collector can make SAH more attractive in terms of effectiveness, economics and building aesthetics.

Optimization of SAH efficiency, physical design and available space can be a good strategy to address this issue. For this purpose, SAH designs with same collector area but different conversion efficiency should be made available. Such designs can provide better choices to customers of different economic levels for matching energy demand with available space. Physical shape of the SAH modules should also be more diverse so that they can be conveniently and aesthetically integrated with existing building structure. Commercial SAH panel for windows and walls is developed by some manufactures (www.grammer-solar.de; http://www.cansolair.com/). However, such designs should be more versatile for extensive use in different building designs. Region-specific conventional/traditional building designs should be considered while developing SAH designs. Modular designs with varying efficiency and also compatible with region-specific building structure can lead to popularization and wider use of SAH.

4.3 Annual utilization

Basically two factors, viz., (a) available solar radiation and (b) space heating requirement of consumers, determine the annual operating hours of SAH. Similar to spatial and temporal variations of solar radiation, annual energy requirement for space heating also depends on diurnal and seasonal variations in ambient temperature as well as geographic location. Usually, regions having longer cold period consume more energy in space heating, while the warmer regions require more energy for cooling. Lower utilization of a system generally increases payback period for capital investment and adversely affects customers' interest for procuring such system.

Increasing hours of effective operation during a year is necessary for enhancing marketability of SAH. As mentioned earlier, using heat storage facilities can address diurnal variations in space heating requirement and can indirectly enhance SAH utilization. Another strategy is to use SAH for secondary thermal applications whenever space heating is not required. Thermal energy from SAH can be used for typical secondary applications like drying, desalination, etc. (Qiblawey and Banat 2008; Sreekumar 2010; Fuller 2007). Considering uncertainty of driving energy source and varying necessity, such strategies can increase useful energy gain from SAH during a year.

Researchers have investigated such strategies for better utilization of SAH. Drying is the most common and simple application of SAH. Drying of agricultural, textile and marine products using different designs of SAH is established by researchers (Abdullah 2005; Palaniappan and Subramanian 1998). Similarly, use of SAH for other applications like desalination or air conditioning is also investigated by researchers (Yıldırım and Solmus 2014). In order to convert salt or brackish water into potable water, fossil fuel-based desalination process is being practised by many courtiers facing scarcity of fresh water. Yıldırım and Solmus (2014) theoretically investigated performance of a solar powered humidification–dehumidification desalination system for different climatic conditions of Antalya, Turkey. The double-pass solar air heater heats up the ambient air for humidification with sea or brackish water which is then passed through the dehumidifier for condensation resulting in fresh water. Humidification–dehumidification (HDH) technique-based systems operate on atmospheric pressure and can be modular facilitating increase in capacity depending on requirement. Jairath et al. (Jairath et al. 2015) investigated thermodynamic performance of a solar air conditioning system using flat plat collector and booster mirror. The study revealed that incorporating vacuum solar collector improves the performance of a direct expansion air-conditioner system. Use of SAH in secondary applications can substantially reduce conventional energy consumption during summer. However, appropriate site-specific integrated designs are required for need-based selection of SAH application among different ones, e.g., drying, cooling or space heating.

Solar energy-based integrated systems for heating, cooling, dehumidification, etc., can (a) compensate lower seasonal requirement of solar air heater, (b) smoothen the variation of the output and (c) reduce the idle period of the SAH. Whaley et al. (2014) report functioning of such integrated system for water and space heating, cooling and dehumidification application for domestic purposes. Here, flat plate collectors and liquid desiccants, namely lithium chloride solution, are used. The system has an absorber and a regenerator-cum-air heater as two heat/mass exchangers. Absorber provides indirect cooling and dehumidification, and the regenerator-cum-air heater performs heating function. In this system, air is indirectly heated using the water–air heat exchanger and the hot air is re-circulated during winter months. Integrated solar thermal system providing heating, cooling and dehumidification can be more effective in countries receiving low winter radiation like Australia.

Figure 9 demonstrates the use of SAH in subsidiary applications. SAH designs should be capable of easy integration with secondary hot air applications like drying

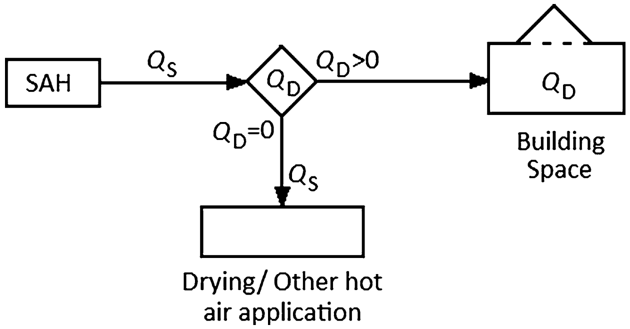


Fig. 9 Block diagram of integration of SAH with other drying/hot air application device

of agricultural, marine or textile products. Such adaptability will particularly benefit the users from the regions where space heating requirement is comparatively lower than countries having higher heating degree days. Using SAH output for secondary applications will in turn increase the annual utilization of SAH as well as help in reducing conventional energy consumption and CO_2 emission resulted from conventional practices followed for such applications. Consequently, SAH will be more attractive for all segments of users having different space heating energy requirement across the world.

4.4 Variation in output temperature

Controlling output temperature in SAH is a critical job. Space heating systems are essentially required to maintain ambient temperature around a particular set point (Djongyang et al. 2010; Santamouri 1986). Conventional heating systems are usually provided with different types of temperature controllers, e.g., thermostatic controls and electronic controls. On the other hand, diurnal or seasonal variations of solar insolation cause wide variations in output temperature in SAH and lack of in-built temperature controlling features reduces its applicability in temperature-specific applications.

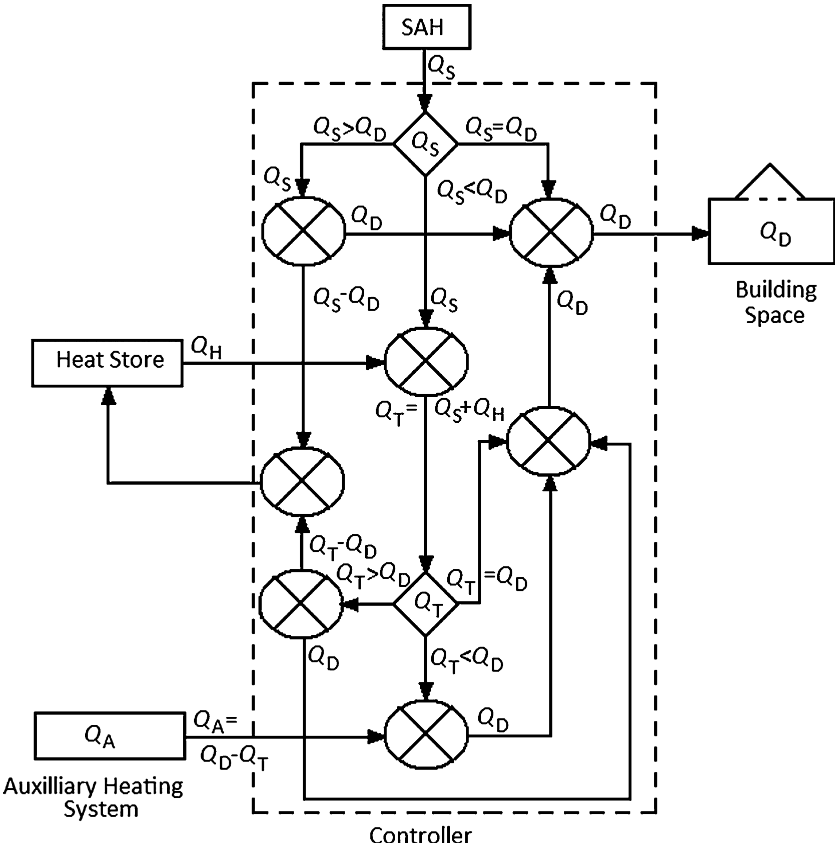
Apart from solar radiation, SAH output is affected by many other environmental and operational parameters, e.g., ambient temperature, wind velocity, relative humidity and air mass flow rate. Appropriate correlation among (a) naturally controlled parameters (solar radiation, ambient temperature, wind velocity, relative humidity), (b) design parameters (geometry, materials) and (c) user controllable operating parameter (mass flow rate, required temperature) is necessary for reducing temperature variations in SAH output (Whaley et al. 2014; Choudhury and Baruah 2014; Ha and Vakiloroaya 2012; Yu et al. 2014). Incorporating in situ automatic temperature control mechanism based on appropriate correlation can enhance SAH applicability and marketability. However, more studies including field-based research are required for developing versatile and user-friendly correlation irrespective of SAH designs.

Although in-built temperature controller is not commonly found with modular or standalone SAH, prospects of using various control strategies in solar thermal applications are studied by researchers for energy conservation purpose (Santamouri 1986; Pasetti and Normey-Rico 2014; Moon et al. 2011; Tahat et al. 2011; Kumar and Kurian 2014; Azzouzi et al. 2011; Hasan et al. 2011; Tasnin and Choudhury 2015). Beizaee et al. (2015) reports the potential of zonal heating control (ZC) systems in UK houses in reduction in fuel used for space heating. During a 8-week investigation in winter among identical houses, zonal control demonstrated more than 11% energy saving. Mahmoud and Hussain (2013) present design approach for a temperature controller for a multi-zone space heating (MZSH) system. Being an interconnected system, MZSH suffers from external and internal disturbances leading to adverse effect on the overall dynamic performance. Numerical simulation of this approach demonstrates its efficiency as compared to other decentralized methods.

A comparative study on different control strategies for solar cooling systems demonstrates potential of close loop control technique for improving performance compared to a conventional system (Ha and Vakiloroaya 2012). Ha and Vakiloroaya (2012) analyzed a new hybrid solar-assisted air-conditioner with specific control techniques, theoretically as well as experimentally. Incorporating an effective temperature controller for refrigerant entering the condenser can improve energy efficiency of the system. Yu et al. (2014) reported testing of a hybrid solar air heating system using active and passive dual function air collectors on a solar demonstration building in University of Science and Technology of China, Hefei China. Experimental results were supported by TRNSYS simulation. The investigation revealed that operation of active and passive operation depends on orientation of rooms for getting best performance.

Studies on using control strategies in solar heating system along with heat pumps are reported by researchers (Mehrpooya et al. 2015; Haller and Frank 2011). Mehrpooya et al. (2015) present the optimum design including economic and technical analysis of a combined solar collector and geothermal heat pump system. The combined system reduces heating energy required for a greenhouse. In this system, fluid entering the evaporator of heat pump is preheated. Haller and Frank (2011) present mathematical relationship for comparing the energetic performance of direct and indirect modes solar collector and heat pump. Effective operation of active or passive mode depends on the irradiation level. Indirect mode is beneficial up to a certain irradiation level depending on operating conditions. Within this limit of irradiance level, transient analysis for

Fig. 10 Schematic diagram of SAH output controller



climates of Zurich and Madrid showed maximum heat delivery to the evaporator of heat pump by indirect mode. A direct to indirect and vice versa switching control acting on the operating conditions can improve overall seasonal performance of combined system.

Schematic diagram of control system for controlling SAH output in terms of output temperature or volumetric air flow to provide required space heating energy is shown in Fig. 10. In general, three basic criteria can be used to govern the control mechanism, viz., (a) energy supplied by SAH (Q_S) is within acceptable limits ($\pm\ \Delta Q_D$) of desired space heating (Q_D), (b) energy supplied by SAH (Q_S) is more than required thermal energy (Q_D), and (c) energy supplied by SAH (Q_S) is less than required thermal energy (Q_D) for space heating. Suitable designs of modular controllers having provisions for convenient integration of SAH with heat store and auxiliary air heating device are required for smoothening diurnal or seasonal output variations. Besides, standard variants of output controller, enabling integration of heat store or auxiliary heating device of different capacity, will be more effective in facilitating need-based selection from users' point of view. Designs of SAH should also be adaptable to mounting of standard variants of such controllers.

5 Conclusions

Solar air heater is a potential device for harnessing solar thermal energy. The primary advantage of this device is its simple technology followed by abundance of required input energy. Reported data show huge consumption of energy for space heating purpose across the world. This also justifies the need of SAH for hot air applications like space heating.

SAH works in a similar principle like solar water heating systems. However, published statistics indicates that growth of SAH installation is far less as compared to water-based systems over the few last decades. Sluggish growth rate of SAH, in spite of ever-increasing energy demand for hot air application due to population growth and improved lifestyle, implies existence of critical issues which need more attention for resolving. In order to fully exploit SAH potential, such issues need to be identified and addressed appropriately.

Common issues affecting growth of SAH use are uncertainty of fulfilling need-based thermal energy requirement and varying seasonal requirements from users' perspective leading to low annual utilization. Availability of suitable installation space and loss of building aesthetics also supplement the sluggish growth rate. Research on low-cost efficient designs with heat storage provision can help in meeting energy need for longer duration and can reduce installation space requirement.

Another important issue is the controlling of output temperature according to users' choice. Variations in output temperatures due to changing environmental conditions are not desirable for temperature-specific applications. More active research is needed for maintaining output temperature through manipulation of operational variables. Field-based studies with different SAH designs can result in more versatile correlations which can be suitably embedded in microcontroller. Research on in situ control mechanism with modular designs supporting diverse hot air applications can enhance applicability as well as annual utilization of solar air heater.

Thus, it can be concluded that, modular designs of SAH in standard variants in terms of efficiency or maximum output energy are necessary for catering the need of users from different economic levels or regions. While designing SAH modules, region-specific traditional building designs should be considered in view of facilitating convenient installation and maintaining existing building aesthetics. Other secondary devices like heat store and control mechanism should also be modular type with different standard capacities. SAH modules with compatible designs with respect to building type, control system, heat store, auxiliary air heating devices and other secondary devices for hot air applications like drying can be expected to result in widespread use of SAH across the world.

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