Different Operational Alternatives of Aquifer Thermal Energy Storage System for Cooling and Heating of a Residential Complex under Various Climatic Conditions of Iran

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Abstract

In this research, a confined aquifer with low groundwater flow was considered to meet the cooling and heating requirement of residential complexes. The complexes were located in the cities of Ahvaz, Ardabil, Bandar Abbas, Esfahan, Kerman, Rasht, Tehran and Zahedan. The complex in Ardabil required mostly heating, the ones in Ahvaz and Bandar Abbas required mostly cooling, whereas the complex in other cities required both heating and cooling. Four different alternatives of aquifer thermal energy storage (ATES) were analyzed in this study. These alternatives were: 1) using ATES alone for cooling 2) for cooling coupled with a conventional refrigeration system or a chiller 3) for heating by employing flat plate solar collectors and 4) for heating by employing flat plate solar collectors and a heat pump. Thermal energy recovery factor and the annual coefficient of performance (COP) of the alternatives were determined. The results showed that, for buildings located in cities with mild climatic conditions (such as Esfahan), where the annual heating and cooling energy requirements are early equal, the use of ATES is highly recommended when employing any of the alternatives considered in this investigation.

Keywords: Aquifer thermal energy storage, climate, solar energy, heat pump

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Nomenclature

\begin{itemize}
\item \textbf{A} \quad \text{area, cross section (}m^2\text{)}
\item \textbf{B} \quad \text{aquifer thickness (}m\text{)}
\item \textbf{C} \quad \text{specific heat (}J/\text{kgK}\text{)}
\item \textbf{COP} \quad \text{coefficient of performance}
\item \textbf{E} \quad \text{energy (}J\text{)}
\item \textbf{h} \quad \text{hydraulic head (}m\text{)}
\item \textbf{K} \quad \text{permeability (}m/s\text{)}
\item \textbf{k} \quad \text{specific permeability (}m^2\text{)}
\item \textbf{P} \quad \text{specific heat capacity (}J/\text{m}^3\text{K}\text{)}
\item \textbf{Q} \quad \text{specific velocity (}m/s\text{)}
\item \textbf{Q} \quad \text{heat (}J\text{)}
\item \textbf{R} \quad \text{wells distance (}m\text{)}
\item \textbf{S} \quad \text{flow source term (}kg/s\text{) and heat source term (}W/m^3\text{)}
\item \textbf{t} \quad \text{time (}s\text{)}
\item \textbf{T} \quad \text{temperature (}K\text{)}
\item \textbf{V} \quad \text{volume (}m^3\text{)}
\end{itemize}

Greek Symbols

\begin{itemize}
\item \textbf{\alpha} \quad \text{diffusivity (}m^2/s\text{)}
\item \textbf{\eta} \quad \text{efficiency or recovery factor}
\item \textbf{\phi} \quad \text{Porosity}
\item \textbf{\lambda} \quad \text{aquifer thermal conductivity (}W/m/k\text{)}
\item \textbf{\rho} \quad \text{density (}kg/m^3\text{)}
\end{itemize}

subscripts

\begin{itemize}
\item \textbf{A} \quad \text{aquifer}
\item \textbf{F} \quad \text{fluid}
\item \textbf{H} \quad \text{heat}
\item \textbf{imp} \quad \text{imposed}
\item \textbf{injection} \quad \text{injection}
\item \textbf{Required, req} \quad \text{required}
\item \textbf{S} \quad \text{specific, solid}
\item \textbf{Storage} \quad \text{storage}
\item \textbf{System} \quad \text{system}
\item \textbf{Withdraw} \quad \text{withdraw}
\end{itemize}

1. Introduction

In relation with energy and buildings, sustainable engineering requires: 1) reduction of the heating and cooling energy needs of buildings to their minimum possible values, 2) reduction of consumption of primary sources of energy to meet these minimum values through
innovative designs of energy conversion systems and the employment of innovative methods to meet the energy demands[1].

Aquifers are underground porous formations containing water. Confined aquifers are surrounded by impermeable layers, called cap rocks and bed rocks[1]. These aquifers are suitable for seasonal thermal energy storage. Seasonal storage of thermal energy in aquifers, as well as the utilization of solar energy and heat pumps are examples of innovative approaches to reduce primary energy demand for heating and cooling of buildings in various climate conditions. Then, it is important to investigate under what climatic conditions do the ATES system has the best performance.

Underground thermal energy storage (TES) for cooling and heating of buildings has been employed in the United States [2-5], Europe [6-11], and other countries [12-15]. Recently, they have become more popular, considering the problems caused by the depletion of fossil fuels and the increase of global warming [16]. The ATES systems are generally considered as economically viable for the seasonal storage of thermal energy [17]. In an ATES, contamination and depletion of groundwater are minimal, since the water withdrawn from aquifer is circulated through a heat exchanger, and is immediately injected back into the aquifer through injection well(s) [13].

The flow of groundwater and heat transfer has been carefully discussed in hydrology. Kim et al. [14] employed thermo-hydraulic modeling to investigate the effects of parameters, such as the distance between the wells, hydraulic conductivity, and the rate of injection/withdraw on an ATES. They used Comsol software for numerical simulation. Sommer et al. [15] determined the thermal performance of large-scale application of ATES using a simplified hydrogeological model. They compared the different zonation patterns and determined the influence of well-to-well distances. Jeon et al. [16] conducted a sensitivity analysis of recovery efficiency in two cases of high temperature ATES system with a single well to
select key parameters. For a fractional factorial design used to choose input parameters with uniformity, they considered the optimal Latin hypercube sampling with an enhanced stochastic evolutionary algorithm. Bloemendal et al. [17] described what optimal and sustainable use of the subsurface would look like in relation to ATES systems. With simulations they showed their impact on the subsurface and described the current way of dealing with these impacts in the Netherlands. Zeghicia et al. [18] assessed the suitability of using heat and cold storage in a single deep geothermal aquifer for district heating and cooling. They used an integrated modelling approach for evaluating the controls on the energy efficiency of high temperature aquifer thermal energy storage (HT-ATES). A parametric study of pressure distribution in a confined aquifer and thermal energy storage in aquifers employing heat pumps reported by Ghaebi et al. [19]. Yi and Dong Ming [20] analyzed the effect of cold water storage in doublet-wells by analyzing the volume change of cold water body within different temperature ranges in different periods. They concluded that cold water storage in aquifers is viable. Gao et al investigated the well position for improving efficiency of thermal energy storage systems [21].

Using the ATES coupled to the other energy supply systems is a common method to satisfying energy demand of buildings. Paksoy et al. [22] utilized an ATES for air-conditioning of a supermarket on the Mediterranean coast of Turkey. This project was the first ATES application carried out in Turkey. Paksoy et al.[23] performed the feasibility study of the ATES system for heating and cooling of Cukurova University Balcali Hospital, in Adana, Turkey. The system stored solar energy in the form of heat and winter coolness in an aquifer. Dincer and Dost [24] proposed a perspective for using the TES in solar applications. One major project in Europe is the German parliament building, which employs TES and solar energy for heating [25]. Caliskan et al. [26] performed thermodynamic assessments of various thermal energy storage systems. They also conducted energy, exergy and sustainability analyses for three various reference conditions. An experimental investigation
of an aquifer thermal energy storage system was conducted in Belgium [27]. In that research, a low temperature ATES system was coupled with heat pumps for heating and cooling of a hospital for a three years period. Ghaebi et al. [28] investigated an ATES in combination with heat pump and solar collector to heating and cooling of a building complex located in Tehran. Reveillere et al. [29] estimated the geothermal contribution to the energy mix of a district heating network over time when using an ATES in Paris region. Their results showed that the ATES would provide 54 GWh per year to the heating system, or geothermal energy providing 70% of the energy mix. Bakr et al. [30] described the analysis of a real case of multiple ATES systems. They considered the efficiency, and the interference among systems installed in the city of The Hague, the Netherlands, in which a total of 19 ATES systems were installed within an area of about 3.8 km² with a total of 76 operating wells. Kranz and Frick [31] discussed the characteristics of the ATES for building cooling of the German Parliament Buildings for almost 10 years. They concluded that by choosing proper operating conditions and design parameters such as the temperature level of the cooling network, or the regeneration temperature of the ATES, the efficiency of the considered system can be increased remarkably.

However to our knowledge, no previous research investigate the effect of climate on the performance of the ATES. In the present research, a suitable confined aquifer was considered to meet the cooling and heating requirements of a residential building complex located in cities of Ahvaz, Ardabil, Bandar Abbas, Esfahan, Kerman, Rasht, Tehran and Zahedan in Iran. The hourly heating/cooling thermal energy requirements of these cities were estimated coming up with peak heating and cooling loads and the annual heating and cooling energy requirements. Because of extremely cold climate, the building complex in Ardabil needed only heating. The building in Bandar Abbas, with extremely hot and humid weather, and also in Ahvaz, with hot and dry weather, required only cooling. The building complex located in
the other cities required both heating and cooling. The size of the aquifer to meet the annual cooling and heating energy needs of the residential complex located in these cities were determined. Ultimately the recovery factor of the aquifer and COP of the system were compared for four different alternatives that were employed for different cities.

2. Climate of Iran

Plateau of Iran has been divided into eight climatic regions [32]. The major cities representing these climates are: Ahvaz, Ardabil, Bandar Abbas, Esfahan, Kerman, Rasht, Tehran and Zahedan.

2.1. Region 1: Ardebil

- Located at high altitude above sea level compared to other regions

- Located at high geographic latitude

- Having low minimum temperature and very cold winters

- Rainfall in this region is mostly snow.

- Exposed to Siberian cold fronts and Mediterranean and Northern Europe humid fronts.

- More than 45 percent of the year needs heating.

2.2. Region 2: Kerman

- Located at high altitude above sea level compared to other regions

- Located at high geographic latitude
- Having low minimum temperature (more than region 1) and very cold and dry winters

- Exposed to Siberian cold fronts and Mediterranean and Northern Europe humid fronts

- About 40-45 percent of the year needs heating.

2.3. Region 3: Esfahan

- Located at relatively low altitudes above sea level

- Having relatively low rainfall

- A fluctuating temperature (cold nights and warm days)

- Cold and dry winters

- About 30-40 percent of the year needs heating.

2.4. Region 4: Rasht

- Located at relatively high geographic latitude

- Having a maximum rainfall than the other regions

- Having minimum temperature about zero

- Mild and wet winters

- About 20 percent of the year needs heating.

2.5. Region 5: Zahedan
- Located at low height over sea level

- Having minimum of rainfall in Iran.

- Having a fluctuating temperature (cold nights and warm days)

- Having a mild and dry climate

- About 10-20 percent of the year needs heating.

2.6. Region 6: Ahwaz

- Located at relatively low height over sea level

- Located at low latitudes

- A semi-humid climate

- About 0-10 percent of the year needs heating.

2.7. Region 7: Bandarabbas

- Located at low latitudes

- A humid climate

- About 0-5 percent of the year needs heating.

2.8. Region 8: Tehran

In this climate, the conditions of the several climates that are mentioned above can be seen together and the heating requirement is a combination of one in the climates of 3, 2, 1 and 4.
Table 1 shows the locations and weather conditions of these cities.

3. Specification of the Residential Complex

The specification of the investigated residential complex has been taken from Ref.[28]. Hourly cooling and heating energy needs of the buildings were estimated using the software HAP 4.41(Carrier). Table 2 shows the peak heating and cooling loads as well as the annual heating and cooling energy requirements of the building complex located in the considered cities.

4. Different Alternatives of Operation

We considered four alternatives to meet the heating and cooling energy requirements of the building complex. These alternatives were: cooling through ATES alone, cooling through ATES augmented with a chiller, heating through ATES and employing flat plate solar collectors, and finally heating through ATES coupled to flat plate solar collectors and heat pump(s). These alternatives are briefly described below[28].

4.1. Cooling through ATES alone

In this alternative, water is withdrawn from the aquifer in winter and after cooling by one or more cooling towers is injected back into the aquifer. The cold water is stored for summer use. In summer, cold water is withdrawn from the aquifer and by going through a heat exchanger the cooling needs of the residential complex is satisfied. Figure 1 shows the system operation in this alternative.
4.2. Cooling through ATES coupled with a chiller

Figure 2 schematically shows the system operation in this alternative. This alternative is employed in cities, with extreme cooling load where the ATES alone cannot meet the cooling requirement. The chiller is selected by considering to refrigeration load, chiller evaporator supply temperature(withdrawn through cold well) and assuming 7°C for chilled water temperature rise from catalogue[34].

4.3. Heating through ATES, employing flat plate solar collectors

Figure 3 shows an ATES coupled with flat plate solar collectors. In this system, solar energy is utilized during the summer months to heat the water withdrawn from the aquifer. The heated water is then injected back into the aquifer. The stored warm water is withdrawn in winter to meet the heating needs of the building[1].

4.4. Heating through ATES and employing flat plate solar collectors and heat pump(s)

In regions, where stored solar energy alone cannot meet the heating requirements, we can employ heat pumps. Figure 4 schematically shows the operation of this alternative.

5. Mathematical formulation

Thermo-hydraulic analysis of the aquifer performance requires calculation of the groundwater flow and the temperature distribution in the aquifer and its surrounding layers. In this section, theoretical principles of water flow and heat transfer phenomena for calculating temperature distribution inside of the aquifer are explained. The coupled
groundwater and heat flow are governed by the partial differential equations describing mass and energy balances in the aquifer \[1\].

Aquifer is a porous medium. The continuity equation in a porous medium may be expressed by the following equation \[35\]:

\[
\left[ \frac{\partial (\rho \phi)}{\partial t} + \nabla \cdot (\rho \vec{q}) \right] dV = S_f
\]  

(1)

where \(S_f\) is related to source/sink term inside the porous medium and \(\vec{q}\) is a flow flux vector.

It is obtained from the Darcy’s equation:

\[
\vec{q} = -K \nabla h
\]  

(2)

This equation is the governing equation for the flow in a porous medium. In this equation \(K\) is the aquifer permeability.

Pressure drop between the wells is calculated from the following equation \[35\]:

\[
\Delta h_{sp} = \frac{Q}{2 \pi K b} \ln \frac{r_o}{r_W}
\]  

(3)

\(r_o\) and \(r_W\) are half of the distance between wells and the well’s radius, respectively.

The equation for heat transfer (conduction and convection) is derived by applying the energy conservation principle in a porous medium \[36, 37\]:

\[
p_s \frac{\partial T}{\partial t} = \nabla^2 (\lambda T) - (\rho c)_f \vec{q} \cdot \nabla T + S_H
\]  

(4)

\[
p_s = (\rho c)_f \phi + (\rho c)_s (1 - \phi)
\]  

(5)

where \(p_s\), \((\rho c)_f\) and \((\rho c)_s\) are heat capacities per unit volume of aquifer, water, and the pebbles, respectively. In this equation, \(T\), \(q\) and \(S_H\) are temperature, specific velocity and energy source/sink terms inside the aquifer, respectively, while \(\lambda\) is a combined ratio that is a function of the thermal conductivity of water, pebbles and aquifer porosity\[28\]:
\[ \lambda = \phi k_f + (1 - \phi) k_s \]  \hfill (6)

Thermo-physical properties of water and aquifer were used from Ref.[28].

Heat transfer phenomena within the upper and lower surrounding layers of the aquifer is mainly conduction. Therefore, we have[28]:

\[ \frac{\partial T}{\partial t} = \alpha \nabla^2 T \]  \hfill (7)

6- Numerical Modeling

The numerical modeling including solution method, meshing, initial and boundary conditions and model assumptions have been comprehensively investigated in Ref.[28].

7. Discussion of the Results

7.1 Model verification

The model has been verified as discussed in Ref.[28].

7.2. Using different alternatives of ATES for heating and cooling of the selected cities

For modeling and design, initial data are needed as the inputs. These input data are given in the Table 3.

Design simulation is carried out as explained in Section 5. The results of the design simulation are listed in Table 4.
In air conditioning systems, COP is an important factor for performance evaluation. As it is seen in the Equation 12, COP is equal to the amount of the annual heating/cooling requirement divided by the total power consumption of the system such as pumps, cooling towers fans, heat pumps and etc. The pump embedded into the aquifer should have the power to overcome all the pressure losses through the pipes, heat exchanger(s) and inside of the aquifer. For an accurate assessment, it is assumed that the piping and water transmission system on the surface are the same for all cities. The pressure losses were determined considering 250m of straight pipes, 10 elbows, a pipe diameter of 10cm, a diameter of 2.5cm and a length of 5m for the tubes in the shell and tube heat exchanger, and finally 45m for the depth of the aquifer wells. Table 5 shows the pressure losses in different alternatives for various cities.

7.2.1 ATES with cooling alone

Figure 5 shows the annual power consumption for different cities. As it seen, the annual power consumption is the highest value in Bandar Abbas due to high cooling requirements and high injection/withdrawal flow rates and high pressure losses. As the result, the power consumptions by the pump and the cooling tower fans are higher in this city compared to the other cities.

Figure 6 shows the recovery factor and COP for this alternative. Both of $\eta_A$ and COP for Esfahan are higher than Bandar Abbas. Groundwater temperature in Esfahan is lower than Bandar Abbas. This makes the heat transfer from the aquifer located in this city will be lower than the one located in Bandar Abbas.

7.2.2. Coupling of ATES with chiller for cooling
The annual power consumption for this alternative is shown in Figure 7. Similar to the cooling alone alternative, the power consumption by the pumps, chiller and the fans in Bandar Abbas is higher than the same system employed in the other cities.

The recovery factor ($\eta_A$) and the COP in this alternative are shown in Figure 8. As mentioned above, $\eta_A$ in Esfahan is higher than the one in the other cities. This is due to lower groundwater temperature inside of the aquifer in this city. The COP for Esfahan is also high. When compared with the cooling-alone alternative, COP is less for this alternative, because of the extra power consumption by the chiller.

7.2.3. Heating by employing flat plate solar collectors

Figure 9 shows the power consumption of the system under this alternative for different cities. It is seen that the power consumption of the ATES system designed for Ardabil is higher than the one for the other cities. This is due to a higher injection/withdraw water flow rate in this city.

Figure 10 shows $\eta_A$ and COP in this alternative. The temperature difference between the injection and the groundwater temperatures is too high. Then heat losses in this alternative are higher than the other considered alternative employed for heating. Due to a higher temperature difference inside of the aquifer located in Ardabil, there is more heat dissipation. As the result, the recovery factor is lower than the one in the other cities. The COP is also lower in Ardabil because of higher power consumption.

7.2.4. Heating by coupling of ATES with flat plate solar collectors and a heat pump
Figure 11 shows the power consumption of the ATES system in this alternative. Due to a higher pressure drop compared to the solar heating alternative, the power consumption is higher in this alternative.

Temperature difference between the injected and the groundwater is lower in this alternative. When compared with the other heating alternative, the recovery factor $\eta_A$ is higher for all the cities (Figure 12).

8. Conclusions

In this study, the performance of an ATES under four different operational alternatives were evaluated for different climates of Iran, using a numerical simulation. These alternatives were: 1) ATES for cooling alone, 2) ATES coupled with a chiller for cooling, 3) ATES coupled with flat plate solar collectors for heating, and 4) ATES coupled with flat plate solar collectors and heat pump for heating. The cities of Ahvaz, Ardabil, Bandar Abbas, Esfahan, Kerman, Rasht, Tehran and Zahedan were selected as representative of the eight climatic conditions of Iran. A residential building complex was considered and was assumed to be located in any of these cities. The peak heating/cooling demands as well as the annual heating/cooling energy needs of the complex were estimated under the climatic conditions of these cities.

The following concluding remarks can be made in this investigation:

- In the ATES for cooling alone alternative, the recovery factor and COP of the system for Esfahan were higher than the other cities.
- In the ATES coupled with a chiller for cooling, the recovery factor and COP of the system for Esfahan were both higher than the other cities.
In the ATES coupled with flat plate solar collectors for heating alternative, the recovery factor and COP of the system for Esfahan were higher than the other cities.

In the ATES coupled with flat plate solar collectors and a heat pump for heating alternative, the recovery factor and COP of the system for Esfahan were higher than the other cities.

For large buildings located in cities with mild climatic conditions, where the annual heating and cooling energy requirements are nearly the same, the use of the ATES is highly recommended when employing any of the alternatives considered in this investigation and discussed above.

References


[34] www.ssi.co.ir (Accessed 30 October 2016)


Figure Captions:

Figure 1 Cooling through ATES alone a) Summer b) Winter

Figure 2 Cooling through ATES augmented with chiller(s) a) Summer b) Winter

Figure 3 Heating through ATES, employing flat plate solar collectors a) Summer b) Winter

Figure 4 Heating through ATES and employing flat plate solar collectors and heat pump(s) a) Summer b) Winter

Figure 5 Comparison of annual power consumption for the cooling-alone alternative

Figure 6 Comparison of $\eta_A$ and COP for the cooling-alone alternative

Figure 7 Comparison of power consumption for ATES coupled with a chiller

Figure 8 Comparison of $\eta_A$ and COP for ATES coupled with a chiller for cooling

Figure 9 Power consumption for the ATES, employing flat plate solar collectors for heating

Figure 10 Comparison of $\eta_A$ and COP for the ATES, employing flat plate solar collectors for heating

Figure 11 Power consumption for the ATES coupled with flat plate solar collectors and a heat pump

Figure 12 Comparison of the $\eta_A$ and COP for the ATES, coupled with flat plate solar collectors and a heat pump
Table Caption:

Table 1 Weather conditions of the selected cities of Iran [33]
Table 2 Heating and cooling requirement of the residential complex in the selected cities
Table 3 Input data for design of the ATES system
Table 4 Results of the design
Table 5 Pressure losses in the aquifer to be employed in different cities
Figure 1

Building

Heat Exchanger

Aquifer

Cold Well    Warm Well
Figure 3

a) Aquifer Cold Well Warm Well

b) Figure 3

Solar Collector

Building

Heat Exchanger
Figure 4

Figure 5
Figure 6

- Recovery Factor (%)
- COP

Ahvaz | Ardabil | Bandar Abbas | Esfahan | Kerman | Rasht | Tehran | Zahedan
--- | --- | --- | --- | --- | --- | --- | ---
56 | 58 | 60 | 62 | 64 | 66 | 68 | 70

Figure 7

- Power Consumption (TJ)

Ahvaz | Ardabil | Bandar Abbas | Esfahan | Kerman | Rasht | Tehran | Zahedan
--- | --- | --- | --- | --- | --- | --- | ---
5 | 7 | 6 | 4 | 3 | 2 | 1 | 0
Figure 10

![Graph showing Power Consumption (TJ) for different cities.](chart10)

Figure 11

![Graph showing Recovery Factor (%) and COP for different cities.](chart11)

Figure 12

![Graph showing Comparison of Recovery Factor and COP for different cities.](chart12)
**Tables:**

### Table 1

<table>
<thead>
<tr>
<th>City</th>
<th>Latitude(°)</th>
<th>Longitude(°)</th>
<th>Elevation (m)</th>
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### Table 2

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### Table 3

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<tr>
<td>ATES + Solar + Heat Pump</td>
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### Table 4

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### Table 5

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### Biographies

**Hadi Ghaebi** is assistant professor in the Mechanical Engineering faculty of the Mohaghegh Ardabili University, Ardabil, Iran. He received his PhD degree from the Sharif University of Technology, Tehran, Iran in 2014. His research areas include thermal system design and optimization, renewable energy technologies, net zero energy buildings and hydrogen and fuel cells.

**Mehdi Bahadorinejad** received his PhD degree in Mechanical Engineering from the University of Illinois, USA, in 1964, and is currently Professor of Mechanical Engineering at Sharif University of Technology, Tehran, Iran. His research interests include natural cooling systems, solar energy utilization, environmentally- compatible energy systems, development of indigenous technology, application of scientific-spiritual thinking to social problems, entropy and awareness and engineering ethics and engineering of ethics.

**Mohammad Hassan Saidi** is Professor in the School of Mechanical Engineering at Sharif University of Technology, Tehran, Iran. His current research interests include MEMS, heat transfer enhancement in boiling and condensation, modeling of pulse tube refrigeration, vortex tube refrigerators, indoor air quality and clean room technology, energy efficiency in home appliances and desiccant cooling systems.