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Toward residential building energy conservation through the Trombe wall and ammonia ground source heat pump retrofit options, applying eQuest model

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Abstract. The aim of this research is to apply the eQuest model to investigate the energy conservation in a multifamily building located in Dayton, Ohio by using a Trombe wall and an ammonia ground source heat pump (R-717 GSHP). Integration of the Trombe wall into the building is the first retrofitting measure in this study. Trombe wall as a passive solar system, has a simple structure which may reduce the heating demand of buildings significantly. Utilization of ground source heat pump is an effective approach where conventional air source heat pump doesn't have an efficient performance, especially in cold climates. Furthermore, the type of refrigerant in the heat pumps has a substantial effect on energy efficiency. Natural refrigerant, ammonia (R-717), which has a high performance and no negative impacts on the environment, could be the best choice for using in heat pumps. After implementing the eQUEST model in the said multifamily building, the total annual energy consumption with a conventional R-717 air-source-heat-pump (ASHP) system was estimated as the baseline model. The baseline model results were compared to those of the following scenarios: using R-717 GSHP, R410a GSHP and integration of the Trombe wall into the building. The Results specified that, compared to the baseline model, applying the R-717 GSHP and Trombe wall, led to 20% and 9% of energy conservation in the building, respectively. In addition, it was noticed that by using R-410a instead of R-717 in the GSHP, the energy demand increased by 14%.

Keywords: retrofitting measures; Ground Source Heat Pump (GSHP); R-717; R-410a; Trombe wall; eQUEST

1. Introduction

Residential buildings are one of the main energy consumers in the United States. In 2014, the residential sector approximately consumed 23 exajoules (EJ) of energy, which accounts for 22 percent of U.S. total energy demand (EIA 2015a). Space heating and air conditioning account for 50 percent of the total energy consumption of households (EIA 2015b). Ataei *et al*. (2015) developed a model for water and energy conservation in a building. Kim (2014) investigated the energy self-sufficiency of office buildings in four Asian cities.

By developing an eQUEST model, this research endeavors to reduce the energy consumed by

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heating and air conditioning in multifamily low-rise buildings-by adopting the following retrofitting measures: Trombe wall and ammonia ground source heat pump. Trombe wall, an energy-efficient passive solar system (Balcomb 1992, Sun *et al.* 2011, Stepler 1980, Yilmaz and Basak Kundakci 2008, Jie 2007a) is divided into two categories: unvented and vented. Unvented Trombe wall has a simpler structure, which consists of a masonry mass wall, a glazing and an air space. The mass wall has a high absorption coefficient (absorptance) to absorb and store the solar radiation during the day substantially and it conducts the stored heat slowly through the living space. It also has low emissivity for reducing stored heat emission. The glass prevents the escape of radiant heat from the warm surface of the storage wall, it also impedes the heat loss from the warm surface of the mass wall (Koyunbaba and Yilmaz 2012). Double or even triple glazing windows are more effective because the air space (cavity) between glazing and wall traps heat within the air space thus reducing heat loss. The vented Trombe wall (Guohui 2006, Zamora and Kaiser 2009, Khedari *et al.* 1998, Jie *et al.* 2007b) is similar to the unvented one. However, the warm air circulates in the air space by fans or free ventilation and allows in more efficient heat conduction. Collection of sunlight during summer is a downside of the Trombe wall because it increases the cooling load of the building. Nevertheless, installation of overhang can considerably make up for this disadvantage.

Trombe wall performance has been modeled by experimental-numerical methods (Shen *et al.* 2007, Koyunbaba *et al.* 2013, Zrikem and Bilgen 1987) and also by simulation software (Ellis 2003, Sami and Gassman 2006) such as EnergyPlus (http://www.eere.energy.gov/buildings/energyplus/) and eQUEST (http://www.doe2.com/equest/). Bojic *et al.* (2014) simulated a house by EnergyPlus, GenOpt (http://simulationresearch.lbl.gov/GO/) and parametric algorithm in order to reveal the annual amount of energy conservation. Moreover, they found the optimum thickness of the Trombe wall core layer in the winter by implementing Trombe wall. They found out that the integration of Trombe wall into the house led to 20% of annual energy saving and the desirable thickness of the Trombe wall core layer simply depended on the energy source of the heating system, which for the electrical heating and natural gas core layer thickness equaled to 0.35m and 0.25m, respectively. Irshad *et al.* (2014) by TRNSYS software (http://www.trnsys.com), compared the energy conservation, CO_2 emission and cost savings in a single zone building which was integrated with Trombe wall and Photovoltaic in three scenarios: air filled gap single glazing, air filled gap double glazing and finally argon gas filled gap double glazing. The results indicated that the argon gas filled gap double glazing scenario had the minimum amount of energy consumption and CO2 emission, followed by the air filled gap double-glazing and air filled gap single glazing. Sacht *et al*. (2011) simulated a building with the Eco-Efficient Refurbishment façade system by Design Builder software (http://www.designbuilder.co.uk) in four climates of Portugal. This model was integrated with two types of double-glazing and Trombe walls. The results demonstrated that, Design builder software was an adequate tool to simulate the passive solar systems and integration of Trombe walls in all façade types led to lower energy demand in comparison with Portuguese energy building performance regulation (RCCTE) standards. They also concluded that the Trombe wall increased the cooling load by 16% to 40% during the summer. However, by installing shading systems such as the overhang, this amount of energy increment could decrease. Finally, the results depicted that adopting one or two Trombe walls in façade modules, led to identical effects on heating energy consumption in milder climates indicating that the second Trombe wall does not have any effect on energy conservation in milder climates.

The second presented measure in this research for energy demand reduction is ammonia (R-

717) ground source heat pump (GSHP). GSHPs are considered renewable HVAC (Heating, Ventilation and Air-conditioning) systems and their worldwide use in residential buildings have been flourished in recent decades (Bose *et al*. 2002). GSHPs have a higher Coefficient of Performance (COP) in comparison with conventional air source heat pumps (ASHP) owing to the higher ground temperature in the winter and lower ground temperature in the summer from ambient air temperature. The performance of NH_3 refrigerant is higher than the plethora of refrigerants (Riffat *et al*. 1997) and leads to increased performance of GSHP. Furthermore, ammonia has zero Global Warming Potential (GWP) and zero Ozone Depleting Potential (ODP) and consequently is considered an environmentally friendly refrigerant.

Analysis of GSHPs has been conducted by simulation applications such as TRNSYS and EnergyPlus in a number of research studies. Safa *et al*. (2015) modeled a house with horizontal ground heat exchanger (GHE) by TRNSYS. Results indicated that by a variety of load temperatures from 8.5℃ to 12.4℃ and source temperatures from 19.2℃ to 17.8℃, the Cooling COP of GSHP changed to 4.9 and 5.6, respectively. In early winter, when the entering load and entering source temperatures were between 44.4℃ and 41.5℃ and 2.7℃ to 5.48℃, the heating COP was between 3.05 and 3.44 respectively. In late winter, when entering load and entering source temperatures were between 48.5℃ and 45.5℃ and -2.36℃ to 0.2℃, the heating COP was between 2.78 and 2.98. The results also demonstrated that the installation of a temperature controller thermostat in the buffer tank conserved 28% energy. Cho and Mirianhosseinabadi (2013) investigated and compared several popular simulation programs for GSHPs modeling such as DOE-2 (http://www.doe2.com), eQUEST, TRNSYS and EnergyPlus. They depicted the advantages and disadvantages of these applications for GSHPs performance in buildings. Henceforth, they simulated a residential building by EnergyPlus and the results were compared to the monthly bill data for evaluation of data accuracy. The results indicated a discrepancy between simulation and bill data, especially in the cold season, because of the inconsistent using of the heating system by occupants, whereas EnergyPlus assumes the heating system is used consistently to provide the comfort conditions.

The baseline model of this study is a residential building (located in Dayton, Ohio, United States) with a conventional air source heat pump (ASHP) system. The eQUEST model, calculated the annual energy demand of the building. The results were compared to the monthly bill data to check data accuracy. Thereafter, Trombe wall and R-717 GSHP as retrofitting measures were presented in two different scenarios and the total annual energy consumption, CO_2 emission and cost of energy consumption were calculated. In another scenario, R-410a is substituted for R-717 in GSHP to illustrate the effect of using R-717 on energy consumption as an alternative in heating and air conditioning systems.

2. Baseline model (R-717 ASHP)

The baseline model is a U-shaped three-story building with zero azimuth degree, situated in Dayton, Ohio. The gross area of the building is 1536 m^2 with 3 m height from floor to floor. The gross area of building glazing is about 40% of each side gross area due to equilibrium of daylighting and air-conditioning loads (ASHRAE 2010). The building is shaded from east and west by the neighboring buildings, thus only north and south façades have glazing. The specifications of north and south façades glazing include triple clear air gap filled gas glasses, framed aluminum integrated with 92 cm overhang for reducing cooling load during summer. Only

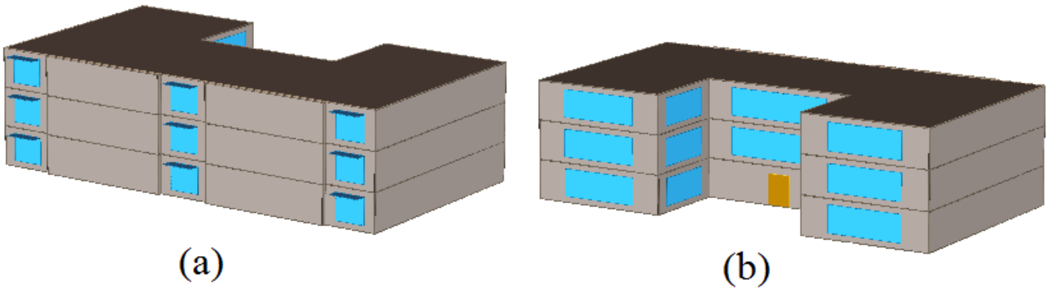

Fig. 1 The U-shaped building in eQUEST model: (a) The 3-D south- view, (b) The 3-D north-view

Table 1 The specifications of building walls, glazing and door

	Type	U-Value (W/m^2.K)	Thickness (mm)
Walls	Ceiling	2.91	13
	Exterior	0.18	381
	Ground Floor	0.25	508
	Interior	2.28	26
	Internal Floor	1.33	101
	Roof	0.24	308
Glazing	Façade	U-Value (W/m^2.K)	Gross Area (m^2)
	North	2.00	175.6
	South	2.00	46.8
Doors	Façade	U-Value (W/m^2.K)	Area (m^2)
	North	4.65	4.5

Table 2 The monthly energy consumption of baseline model from the monthly bills and from the eQuest modeling

Month	Monthly bill data (MWh)	eQuest (MWh)	Difference (%)
Jan	13.45	13.75	2.2
Feb	9.29	9.6	3.3
Mar	8.03	8.23	2.5
Apr	6.47	6.55	1.2
May	6.7	6.8	1.5
Jun	7.78	7.99	2.7
Jul	8.46	8.73	3.2
Aug	7.96	8.21	3.1
Sep	6.9	7.1	2.9
Oct	6.27	6.36	1.5
Nov	7.54	7.67	1.7
Dec	10.99	11.3	2.8

the north side has a metal door with 4.5 m^2 gross area. The specifications of building walls, glazing and door such as U-value and gross area are depicted in Table 1. The three dimensional (3-D) view

Table 3 The annual energy demand, cost of energy consumption and CO_2 emission of baseline model with R-717 conventional air heat pump (R-717 ASHP)

Cooling	Heating	A/C	Total
Annual energy demand (MWh/yr)			
9.72	13.29	44.24	102.3
Annual cost of energy consumption ($/yr)			
972	1329	4424	10230
Annual CO_2 emission (g/yr)			
4860	6645	22120	51150

of the building in eQUEST is featured on Fig. 1.

The building monthly energy consumption data and eQuest modeling are depicted in Table 2. The arithmetic average of the difference between real values and eQuest results in each month is 2.4 percent with an acceptable discrepancy and adaptation of real simulation of residential buildings.

The baseline model has a convectional air source heat pump (ASHP) with ammonia refrigerant. The ambient air is the heat sink for heating in the winter and heat rejection source in the summer. The cooled or heated air is recirculated completely to provide comfort all year long. Table 3 shows the annual energy demand, cost of energy consumption and CO_2 emission of the baseline model. The results were categorized into four sections of energy demand and expressed as follows:

- The building load for cooling in the summer (Cooling),
- The building load for heating in the winter (Heating),
- The sum of the cooling, heating and accessories of air-conditioning system loads (A/C),
- The annual sum of the air-conditioning, equipment and lighting loads (Total).

The miscellaneous equipment and lighting loads are constantly changing in the air-conditioning system; therefore, they have been eliminated from the analysis of results.

3. GSHPs

Ground source heat pumps (GSHPs) have the significant potential to decrease cooling and heating energy demand in air-conditioning systems considerably (Philappacopoulus and Berndt 2001) and using of GSHPs has the annual growth rate in about 10% through the world (Sarbu and Sebarchievici 2014). According to ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers) standard (2013), GSHPs are categorized into three major groups, as follows:

- The ground-water heat pump (GWHP) systems
- The surface-water heat pump (SWHP) systems
- The ground-coupled heat pump (GCHP) systems

The GCHP systems based on ground heat exchanger (GHE) are classified into two major groups, including horizontal ground heat exchanger (HGHX) and widely used vertical ground heat exchanger (VGHX).

eQUEST as a dynamic energy modeling application simulates performance of GSHP systems by a developed g-function algorithm, which is a two-dimensional numerical model of a borehole and was formulated by Yavuzturk and Spitler (1999).

In steady-state condition, the total heat transfer rate per unit length of ground heat exchanger could be obtained from Eq. (1).

$$Q = \frac{T_f - T_b}{R_b} \tag{1}$$

The temperature of the heat pump circulating fluid (T_f) is the mean temperature of the ground heat exchanger inlet and outlet fluid temperatures.

$$T_f = \frac{T_{fout} - T_{fin}}{2} \tag{2}$$

The borehole thermal resistance is defined as R_b and consists of three terms, including the grout conduction thermal resistance (R_G), the GSHP circulating flow convection thermal resistance ($R_{Convection}$) and the pipe conduction thermal resistance (R_p).

$$R_b = R_G + R_{Convection} + R_p \tag{3}$$

The grout conduction thermal resistance (R_G) is expressed as Eq. (4), and β_0 and β_1 are shape factor coefficients and equal to 20.100377 and -0.94467, respectively (Paul 1996). The term of $k_G$is the grout thermal conductivity and D_b and D_p are the borehole and pipe diameter, respectively.

$$R_G = \frac{1}{k_G \beta_0 (D_b / D_p)^{\beta_1}} \tag{4}$$

The third term of Eq. (3) is the convection thermal resistance ($R_{convection}$) of VGHX circulating flow. In Eq. (3), h_{in} is the convection coefficient, which is obtained from Eq. (6).

$$R_{Convection} = \frac{1}{2\pi D_{in} h_{in}} \tag{5}$$

The convection coefficient based on the pipe inside diameter (h_{in}), is a function of Reynolds number (Re) and Prantl number (Pr) and the amount of constant number (n) equals 0.4 and 0.3 for heating and cooling, respectively, k_G is the VGHX pipe thermal conductivity.

$$h_{in} = \frac{0.023 Re^{0.8} Pr^n k_f}{4\pi k_p} \tag{6}$$

The third term Eq. (3) represents the pipe conduction thermal resistance (R_p) and is calculated by the following formula: Eq. (7).

$$R_p = \frac{In(D_{out} / D_{in})}{4\pi k_p} \tag{7}$$

The total heat transfer per VGHX unit length can be obtained by calculating borehole thermal resistance (R_b).

The specification and the size of the VGHX are estimated from building heating and cooling loads, refrigerant type of heat pump, ground soil properties and the annual mean temperature of

Table 4 Thevertical ground heat exchanger (VGHX) specification

GHX	Type		Vertical
	Arrangement		2×4
	Pipe	Type	Poly Ethylene
		O.D	48(mm)
		I.D	39(mm)
		Conductivity	0.398(W/m.K)
Borehole	Depth		76(m)
	Diameter		15(cm)
	Conductivity		1.523(W/m.K)
	U-Tube Leg Separation		56(mm)
	U-Tube Configuration		4
Soil	Type		Coarse Sand 100%
	Moist		10%
Fluid	Type		Propylene Glycol 30%

Table 5 The annual energy demand, cost of energy consumption and CO_2 emission of R-717 GSHP scenario

Cooling	Heating	A/C	Total
Annual energy demand (MWh/yr)			
8.27	8.67	35.3	93.36
Annual cost of energy consumption ($/yr)			
827	867	3530	9360
Annual CO_2 emission (g/yr)			
4135	4335	17650	46680

ambient air. The specification of the vertical ground heat exchanger of the model is identified in Table 4.

3.1 R-717 GSHP scenario

In this scenario, the conventional air source heat pump of the building is changed to ammonia ground source heat pump (R-717 GSHP) and the variation of energy consumption is evaluated by eQUEST model. The type of GSHP is a vertical ground heat exchanger (VGHX), the specification of VGHX is defined in Table 4. The refrigerant in the system is environmentally friendly, R-717 having a high performance, overall performance of GSHP increased considerably. Table 5 shows the annual energy demand, cost of energy consumption and CO_2 emission of R-717 GSHP scenario in four subdivided energy demand sections.

3.2 R-410a GSHP scenario

The R-410a GSHP scenario depicts that R-410a is the refrigerant of the defined ground source heat pump in Table 4. The substitution of R-410a with R-717 is for demonstrating the higher

Table 6 The annual energy demand, cost of energy consumption and CO_2 emission of R-410a GSHP scenario

Cooling	Heating	A/C	Total
Annual energy demand (MWh/yr)			
11.81	10.89	41.23	99.29
Annual cost of energy consumption ($/yr)			
1181	1089	4123	9929
Annual CO_2 emission (g/yr)			
5905	5445	20615	49645

performance of ammonia in comparison with common used HFCs such as R-410a refrigerant. Table 6 shows the annual results of eQUEST modeling and illustrates the discrepancy of results between R-717 GSHP and R-410a GSHP scenarios. Compared to R-717 GSHP scenario the amounts of all four subdivided energy demand sections have been increased, and the increments demonstrate the higher performance of natural R-717 refrigerant.

4. The integration of Trombe wall scenario

The concept of storing solar heat during the day and using it later was developed in the early 1900s, and since then a plethora of experimental investigations on passive solar storage systems has been conducted. Felix Trombe (1972) presented the massive masonry wall on building façades for absorption of sunlight, which was popularized as Trombe wall and as an effective passive solar device. The implementation of the following approaches on unvented Trombe wall led to the conclusion that the Trombe wall performs well in the scale of passive solar storage:

- Multiple (two or more) glazing layers for increment of isolation and trapping solar heat radiant considerably.
- The exterior surface of the masonry wall with lowest emissivity and highest absorptance rate.
- The core of the masonry wall with high storing property.

Trombe wall was simulated by computer in the 70s for the first time, and currently dynamic simulation programs such as DOE-2, EnergyPlus and TRNSYS can simulate Trombe wall. The eQUEST and DOE-2 simulate Trombe walls by using Mull and Reiher (1930) experimental convection correlations applied to convection turbulent flow.

The free convection with the turbulent flow is defined for heat transfer between warm air and the mass wall in the air gap of the unvented Trombe wall. The convention correlation of Mull and Reiher (1930) is expressed as Eq. (8), which is a function of Rayleigh number.

$$Nu = 0.065\left(\frac{Ra}{\Pr}\right)^{1/3} a^{-1/9} \qquad 1.4\times10^{5} \le Ra \le 7.8\times10^{7} \tag{8}$$

Eq. (9) captures the Rayleigh number in the Trombe wall air gap as follows:

The parameters of Eq. (9) are defined as: acceleration of gravity (g), volumetric thermal expansion coefficient (β), hot wall and cold temperatures (T_1) and (T_2) respectively, length of air gap (L), aspect ratio or height of Trombe wall per length of air gap (a) and kinematic viscosity (υ).

$$Ra = \frac{g\beta(T_1 - T_2)L^3}{a\upsilon} \tag{9}$$

The convection coefficient (h_C) is a function of Nusselt number and is calculated by Eq. (10). Nusselt number was obtained from the Eq. (8) initially.

$$h_C = \frac{K_{Tw} Nu}{L} \tag{10}$$

And finally, the net heat flux through the Trombe wall air gap (between the hot wall and cold temperatures) is defined as

$$q'' = h_C(T_1 - T_2) \tag{11}$$

The major part of occupants' required daylighting is provided from the south side of the building in the northern hemisphere and only 60% of the south façade gross area was designated for Trombe wall and required daylighting for dwellers. To eliminate the negative aspect of the Trombe wall (absorption of sunlight in the summer), the overhangs with projection depth of 92 cm

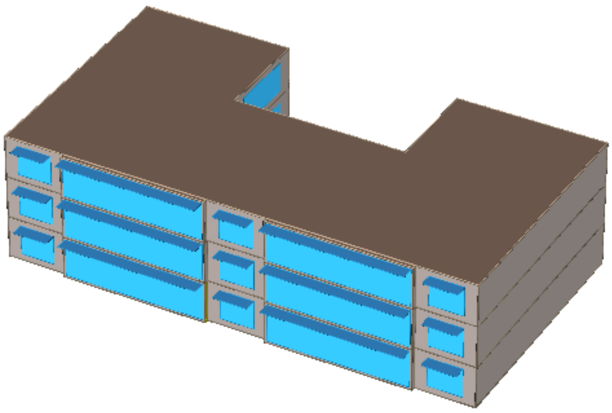

Fig. 2 Trombe walls and the overhangs on the south façade of the building in the eQuest model

Table 7 The specification of integrated unvented Trombe wall

Mass wall	Height	3 (m)
	Thickness	30 (cm)
	Width	20.7 (m)
	Core U-Value	3.38 (W/m^2. K)
	Absorptance	0.98
	Emissivity	0.9
Air gap	Width	15(cm)
	Ventilation	No
Glazing	Type	Quadruple Low-E
	SHGC	0.45

Table 8 The annual energy demand, cost of energy consumption and CO_2 emission of integration of Trombe wall scenario

Cooling	Heating	A/C	Total
Annual energy demand (MWh/yr)			
8.21	8	31.4	89.46
Annual cost of energy consumption ($/yr)			
821	800	3140	8946
Annual CO_2 emission (g/yr)			
4105	4000	15700	44730

were adopted to prevent excessive direct sunlight exposure on the Trombe wall glazing Fig. 2 shows the locations of Trombe walls on the south façade, which were divided into two parts for uniform distribution of daylighting into the room.

Table 7 shows the specification of integrated Trombe wall in the residential building, where given parameters were optimized by the eQuest model to increase performance.

Table 8 depicts the annual energy demand, cost of energy consumption and CO_2 emission of the Trombe wall scenario. The results demonstrate that the integration of the Trombe wall into the building has decreased the heating and A/C energy demand considerably in comparison with previous scenarios.

5. Results and discussion

The results of the eQUEST models indicated that the annual A/C energy demand in the baseline model and R-717 GSHP, R-410a GSHP and Trombe wall scenarios were equal to 44.24 MWh, 35.6 MWh, 41.23 MWh and 31.4 MWh, respectively. Fig. 3 shows the total energy consumption of the baseline model and three scenarios in four subdivided energy sectors, which the baseline model and integration of Trombe wall scenario have the highest and lowest annual amount of A/C energy demand, respectively.

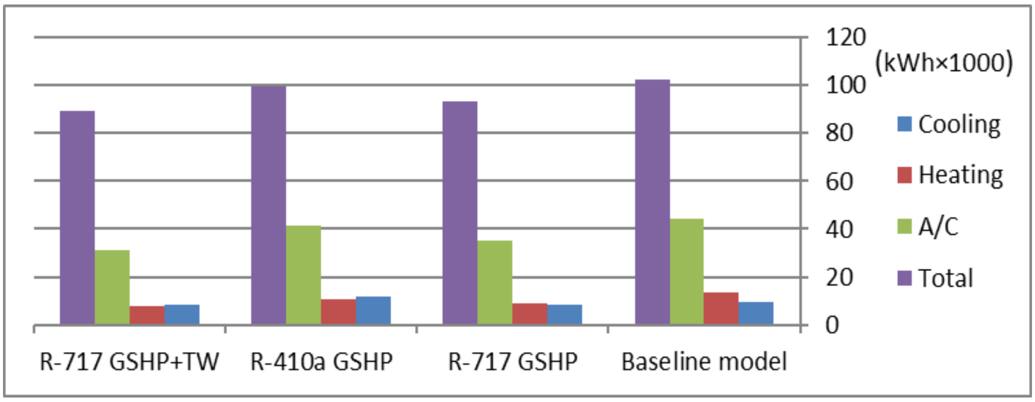

Fig. 3 The annual energy consumption of baseline model and three retrofitting scenarios in four subdivide energy demand sections

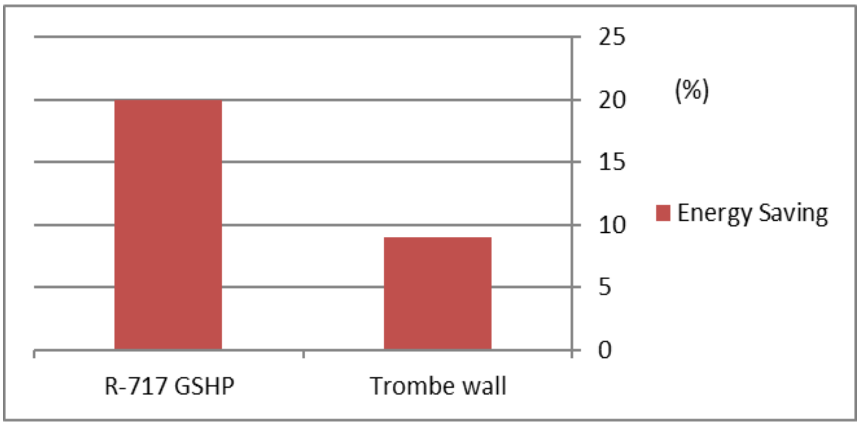

Fig. 4 Percentage of Trombe wall and R-717 GSHP energy conservation

Fig. 4 depicts that, integration of Trombe wall and ammonia (R-717) ground source heat pump as the retrofitting measures conserved in about 9% and 20% of annual A/C energy consumption accordingly.

The comparison of R-717 GSHP and R-410a GSHP scenarios, illustrates the difference of energy consumption between natural R-717 refrigerant and synthetic R-410a (with 4340 GWP) as the refrigerants of GSHP. The eQUEST models demonstrated that the substitution of R-410a for R-717 increased the annual A/C energy demand by approximately 14%.

6. Conclusions

This study modeled a residential building located in Dayton, Ohio by applying the eQUEST model and presented R-717 ground source heat pump and the Trombe wall as two retrofitting measures to decrease annual energy consumption, CO_2 emission reduction, and cost of energy demand. Passive solar Trombe wall is a cost-effective and simple dark masonry structure in residential buildings and is considered an effective retrofitting measure for absorbing sunlight in winter. The ground source heat pumps (GSHPs) have considerable potential to decrease energy consumption due to ground warmer temperatures in the winter and colder temperatures in the summer. Using R-717 refrigerant instead of R-410ais an efficient approach for energy conservation and CO_2 emission reduction in GSHPs.

The results demonstrated that:

• The integration of Trombe walls in 60% of gross area of the south façade conserved 9% of annual A/C energy demand. Only 60% of the total area of the south façade was integrated in the Trombe walls in order to preserve occupants' daylighting and outdoor views.

• Using R-717 GSHP with vertical ground heat exchanger (GHE) instead of conventional R-717 ASHP, led to 20% annual A/C energy savings energy.

• The substitution of R-410a for R-717 in GSHP system increased the energy demand by approximately 14% and this increment demonstrated the higher performance of R-717 compared to R-410a with 4340 GWP amount.

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CC

Nomenclature

a	Aspect ratio, H/L
D_b	Borehole Diameter (m)
D_{in}	Pipe inside Diameter (m)
D_{out}	Pipe outside Diameter (m)
D_p	Pipe mean Diameter (m)
g	Acceleration of gravity (m/s^2)
H	Height of Trombe wall (m)
h_C	Convection coefficient of Trombe wall (W/m^2.K)
h_{in}	Convection coefficient (W/m^2.℃)
k_f	Fluid thermal conductivity (W/m. ℃)
k_G	Grout thermal conductivity (W/m. ℃)
k_p	Pipe thermal conductivity (W/m. ℃)
K_{Tw}	Thermal conductivity of Trombe wall (W/m. K)
L	Length of Trombe wall air cavity(m)
n	Constant
N_u	Nusselt number
P_r	Prantl number
Q	Heat rate per unit length (W/m)
q''	Heat flux (W/m^2)
R_b	Borehole thermal resistance (m.℃)/W)
$R_{Convection}$	Flow convection thermal resistance (m.℃)/W)

R_G	Grout thermal resistance (m.℃)/W)
R_p	Pipe thermal resistance (m.℃)/W)
R_a	Rayleigh number
R_e	Reynolds number
T_1	Hot wall temperature (K)
T_2	Cold wall temperature (K)
T_b	Borehole temperature (℃)
T_f	Fluid temperature (℃)
T_{fin}	Inlet fluid temperature (℃)
T_{fout}	Outlet fluid temperature (℃)
β	Volumetric thermal expansion coefficient (1/K)
β_0, β_1	Shape factor coefficients
υ	kinematic viscosity (m^2/s)