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THEORETICAL EXAMINATION OF ALTERNATIVE REFRIGERANTS FOR R410A IN A GROUND SOURCE HEAT PUMP ACCORDING TO ASHRAE CLASSIFICATION

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ABSTRACT

Today, environmental pollution and global warming have become global threats. The use of renewable energy sources is a rational approach to overcome this problem, and ground source heat pumps also play an important role in this approach. However, the refrigerants used in these systems often have global warming potential values above the specified norms. In this study, using the Engineering Equation Solver package program, the performance values and environmental effects of R410A alternative refrigerants were analyzed theoretically according to ASHRAE safety groups with the help of the data obtained from the experimental study. The results showed that the R32 increases the COP value by 3.1% and reduces the mass flow rate by nearly 35%. It has been calculated that R152a provides the most successful results in the study. R152a provided an 8.5% increase in COP compared to R410A. It has been observed that the operating costs of R452B, R454B and R454C, which are specified as alternative refrigerants by environmental protection agency, are higher than R410A. In the study, it was determined that the R454C has the lowest values in all respects. It has been calculated that using R32 instead of R410A reduces the CO_2 equivalent emissions by approximately 2.54%.

Keywords: *Heat pumps, Ground-source heat pump, R410A, Alternative refrigerants, GWP, First law analysis, COP*

TOPRAK KAYNAKLI BİR ISI POMPASINDA R410A'YA ALTERNATİF SOĞUTUCU AKIŞKANLARIN ASHRAE SINIFLANDIRMASINA GÖRE TEORİK OLARAK İNCELENMESİ

ÖZET

Günümüzde çevre kirliliği ve küresel ısınma global bir tehdit haline gelmiştir. Yenilenebilir enerji kaynaklarının kullanımı bu sorunun üstesinden gelmek için akılcı bir yaklaşımdır ve toprak kaynaklı ısı pompaları da bu yaklaşımda önemli bir yer tutmaktadır. Fakat bu sistemlerde kullanılan soğutucu akışkanlar çoğunlukla belirlenen normların üzerinde küresel ısınma potansiyeline sahiptir. Bu çalışmada Engineering Equation Solver paket programı kullanılarak R410A alternatif soğutucu akışkanların performans değerleri ve çevresel etkileri deneysel çalışmadan elde edilen veriler yardımıyla ASHRAE güvenlik gruplarına göre teorik olarak analiz edilmiştir. Sonuçlar R32'nin, COP değerini %3.1 artırdığını, kütlesel debiyi %35'e yakın düşürdüğünü göstermiştir. Ayrıca çalışmada R152a'nın en başarılı sonuçları sağladığı hesaplanmıştır. R152a, R410A'ya kıyasla COP'ta %8,5'lik bir artış sağlamıştır. Çevre Koruma Ajansı tarafından alternatif soğutucu akışkan olarak belirtilen R452B, R454B ve R454C'nin işletme maliyetlerinin R410A'dan daha yüksek olduğu gözlemlenmiştir. Çalışmada R454C'nin her açıdan en düşük değerlere sahip olduğu belirlenmiştir. R410A yerine R32 kullanılmasının CO_2 eşdeğeri emisyonlarını yaklaşık %2.54 oranında azalttığı hesaplanmıştır.

Anahtar Kelimeler: *Isı pompası, Toprak kaynaklı ısı pompası, R410A, Alternatif soğutucu akışkanlar, GWP, Birinci kanun analizi, COP.*

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1. Introduction

The use of renewable energy sources is an appropriate solution to increase the percentage of energy production and prevent climate change [1]. However, as the use of renewable energy sources is still at limited levels, measures to limit energy consumption are widely applied. Due to important parameters such as cooling and heating load, electricity consumption and external design conditions, which affect the energy consumption of residential conditioning systems, their application varies in each region [2]. Taking advantage of renewable energies in these and similar applications is a rational approach to minimize the effects on the environment. The source of energy mainly used in heating and cooling systems is based on fossil fuels and the related source plays an important role in the increase of global warming.

Ground source heat pump (GSHP) systems, which use the heat under the ground, which is one of the environmental approaches, is one of the topics that have been extensively researched [3–7]. GSHP systems are implemented in two basic installation types, horizontally and vertically, according to the ground heat exchanger (GHE) design. Horizontal GHE is lower in both cost and performance compared to vertical GHE and requires more installation space than vertical GHE. Basically, a GSHP system consists of a heat pump, underfloor heating circuit (or fan unit) and GHE. The thermal energy of the soil is transmitted to the liquid circulating in the soil heat exchanger; this energy is then drawn in and amplified by the heat pump to be delivered to the building via a distribution system such as fan coil units. The system is reversed in the summer and gives off heat to the ground to cool the building. Many scholars have investigated the thermal performance of the GSHP system, either with analytical approaches, experimental methods or semi-analytical solutions combined with numerical methodology [8-10]. However, these studies are commonly associated with GHE performance. Optimization of the components used in these systems and making them compatible with environmental norms is as important as the performance increase expected from the systems. Therefore, minimizing the effects of gases used as the refrigerant in these systems on global warming is of vital importance. In addition to different factors, the effect of hydrofluorocarbon (HFC) refrigerants used in these systems on global warming is quite high. Therefore, EURO-F gas regulations, Montreal protocol and Kyoto protocol have imposed significant restrictions on refrigerants with high global warming potential (GWP) [11,12]. The most widely used HFC refrigerant today is R410A, which is formed by mixing R-32 and R125 in equal proportions. In addition, R404A with a very high GWP value (3992) continues to be used by the heat pump industry despite all warnings.

With the EURO-F gas regulation, significant restrictions have been imposed on refrigerants with a GWP value of 2500 and above as of January 1, 2020. In addition, the prohibition of the use of refrigerants with a GWP value of more than 750 for single split air conditioning systems containing less than 3 kg of refrigerant has been included in the same regulation as of 2025 [13]. For low-capacity air conditioning, heating and cooling systems, options with low GWP, especially refrigerants with similar volumetric capacity to R410A, are limited, and defined refrigerants with a successful coefficient of performance (COP) value and low toxicity are at least slightly flammable [14]. The most important alternative to R410A is the R32, which has a one-third lower GWP and low environmental impact and R32 is an option for replacing R410A in residential conditioning systems [15]. Although R32 was not considered as an alternative in the past because it was classified as slightly flammable compared to R410A and offered higher compressor discharge pressures, R32 is now being re-evaluated due to its low GWP value and good system performance [16,17], [18]. However, many factors such as environmental impacts, safety aspects, applicability and energy efficiency of refrigerants that are planned to be used in place of high GWP refrigerants such as R410A and R404A should be comprehensively considered. Various studies have shown that the heat pump using R32 shows a superior heating capacity and performance at low outdoor temperatures compared to the system using R410A, thanks to its high compressor frequency under harsh weather conditions [19–22]. Pham and Rajendran [23] reviewed the R410A replacement with R32 by compiling test results and safety reviews and concluded that R32 could be presented as the first candidate for the HFC phased plan. In addition, in other studies, R32 is shown as one of the best alternatives to R410A [22,24]. The environmental protection agency (EPA) has classified the R32 as acceptable for use in heat pumps [25].

As it is known, the refrigerants are divided into different safety groups by ASHRAE according to their ignition and toxicity values (Fig. 1). In the safety groups, R32 is in the group as A2L and ASHRAE defines R32 as a slightly flammable refrigerant [16]. Contrary to popular belief, this group classified as slightly flammable does not ignite with a heat source such as a lighter in case of leakage [26]. In addition, studies investigating the leakage status of R32 showed that in the event of a possible leak, the flammable zone was only seen near the leak hole and the duration of the flammable zone was very short [27] and there was no flame spread even if the leak covered the entire room [28]. From the study results one can conclude that the fire risk of R32 is very low under general operating conditions. In addition, R32 offers a lower flammability and lower cost than hydrocarbons (R290 etc.) [17].

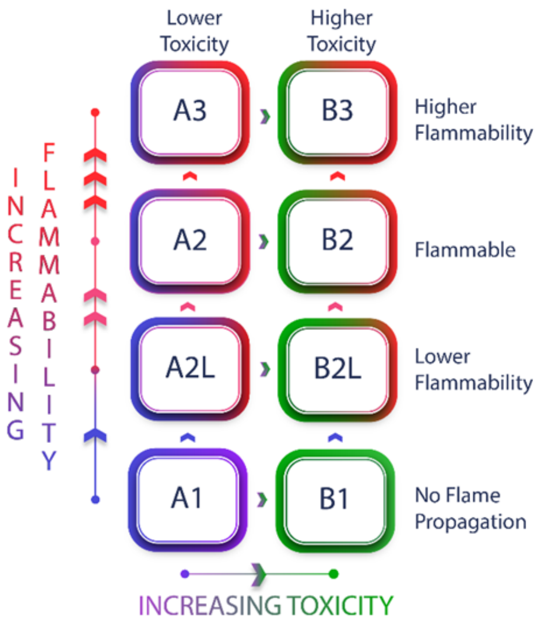


Figure 1. Safety groups of refrigerants according to ASHRAE.

The performance of R32 has been researched and optimized for residential conditioning applications in the literature. In an experimental comparison of R32 and R410A in a vapor-injected heat pump system, it was calculated that R32 could increase the COP and capacity by 9% and 10%, respectively [24]. It is also stated that in an air-to-water reversible unit, R32 increases system efficiency by 7% compared to R410A [29]. Barve et al. [30] stated that R32 has a higher COP than R410A. Mota-Babiloni et al. [31] conducted a comprehensive review of the reasons for the adoption of R32 in residential conditioning systems, especially in the European and US market, and cited the following findings in their study results:

- R32 is a known refrigerant with well-defined properties, and current studies focus on mixing properties of R32 and A2L,
- R32 has a higher heat transfer coefficient and pressure drop than R410A in both evaporation and condensation processes,
- The R32 offers similar system performance to the R410A, but most studies suggest system modifications to avoid high discharge temperatures.

As a result, R32 is less flammable than hydrocarbons and the allowed amount of refrigerant is sufficient for use in current conditioning systems. Its toxicity is inferior to other synthetic liquids and precautions taken for such refrigerants are also applicable for R32.

Apart from R32, there are alternative refrigerants to R410A. For use in residential and low-capacity commercial air conditioning and heat pumps, the EPA lists R452B, R454B, R454C as acceptable alternatives in addition to R32 [22]. Apart from these refrigerants, R290 [25,32], R161 [33], R152a [34], R466A [35] and R1234yf [25,34] are also specified as alternatives for R410A and R404. The properties of the refrigerants mentioned in Tab. 1 are given.

There are various restrictions for alternative refrigerants given in Tab. 1. Although R161 is classified as a flammable fluid, it is incomplete due to the lack of toxicity testing. Only one manufacturer's approval for the use of R454B refrigerant in the scroll compressor limits its use. Because the R454C requires a large compressor and heat exchanger, there are doubts about the cost. R466A is in an early stage of refrigerant testing and its suitability for split systems is unclear [36]. As R290 and R152a are classified as flammable (A2 and A3, respectively), the state of charge, size and use are subject to severe limitations. Although R466A is classified as A1 by ASHRAE, it is not yet listed in EN378 and ISO817 [37]. R1234yf, is one of the potential refrigerants due to its excellent environmental performance [38]. However, in serial tests it has low cooling capacity, high compressor power consumption and low COP value [39,40].

Table 1. Characteristics of alternative refrigerants to R410[16,41–46]

	Chemical Formula	**Composition**	**Safety Class**	**GWP*-AR4***	**GWP*-AR5***	**ODP***	**Crit. Temp.** °C	**Crit. Pressure** Bar	**Boil @ 1,013 Bar** °C	**Density @1,013 Bar - 25ºC**	**AIT*** °C
R410A	R-32/125	50/50	A1	2088	1924	0	71.3400	49.0100	-51.4400	3.0600	x
R404A	R-125/143a/134a	44/52/4	A1	3922	3943	0	72.1200	37.3500	-46.2200	4.1300	728
R466A	R-32/125/13I1	49/11.5/39.5	A1	733	696	0.0100	73.1300	52.8300	-54.0200	3.4000	x
R32	Pure	x	A2L	677	677	0	78.1100	57.8200	-51.6500	2.1900	648
R452B	R-125/1234yf/32	7/26/67	A2L	698	676	0	77.1000	52.2000	-50.6700	2.6800	509
R454B	R-32/1234yf	68.9/31.1	A2L	467	466	0	78.1000	52.6700	-50.4900	2.6400	496
R454C	R-32/1234yf	21.5/78.5	A2L	148	146	0	85.6700	43.1900	-45.4600	3.8500	444
R1234yf	Pure	x	A2L	4	<1	0	94.700	33.8200	-29.4900	4.8500	405
R152a	Pure	x	A2	124	138	0	113.3000	45.1700	-24.0200	2.8100	455
R290	Pure	x	A3	3	3	0	96.7400	42.5100	-42.1100	1.8600	470
R161	Pure	x	A3	12	4	0	102.2200	50.900	-37.6000	2.0100	x

*GWP: Global warming potential, AR4: Intergovernmental panel on climate change fourth assessment report, AR5: Intergovernmental panel on climate change fifth assessment report, ODP: Ozone depletion potential, LVL: Lower flammability limit, AIT: Auto ignition temperature.

Based on the information given above, in this study, the alternatives of the R410A refrigerant used in the GSHP system were investigated and compared with the help of the Engineering Equation Solver (EES) package program, and the system performance and environmental effects were examined. Studies on the subject in the literature are generally related to the comparison of certain refrigerants. Studies showing collectively alternatives to R410A are very limited. In this study, it was aimed to see the alternatives from a different perspective by both comparing the alternatives as a whole and evaluating the performance of the refrigerants according to the ASHRAE classification, and the study was designed in this direction. In addition, the study differs from other studies because it is based on experimental data and a GSHP system is taken as a reference [44,45]. R404 refrigerant, which is one of the separating well-known refrigerants and whose usage is still at a considerable level, was also included in the study. In the study, R32, one of the alternatives of R410A, was discussed and included in the comparison in current alternatives. All values used in the study were simulated using real environment data and GSHP operating conditions were analyzed for 2.5 m and 1 m ground depth, outdoor temperature and 0 °C. With the results of the study, contributing to the reduction of the use of refrigerants with high GWP values such as R410A and R404A by showing the possible effects and supporting their use not only in air source heat pump applications but also in different heat pump systems such as GSHP are among the aims of the study.

2. Material and Method

The data used in the study were obtained from a GSHP system installed in a region in the terrestrial climate zone of Turkey [47,48]. Energy parameters at the temperature points were calculated with reference to the data in the experimental study. The heating capacity of the heat pump is 2.2 kW and consists of basic components such as ground heat exchanger, compressor, condenser, evaporator, expansion valve, circulation pump and four-way valve. The schematic representation of the system is given in Fig. 2.

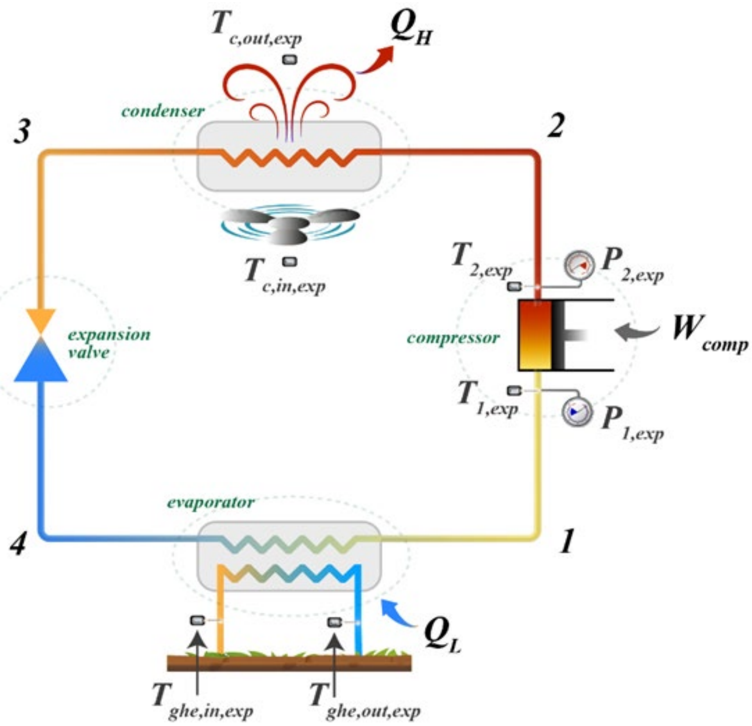


Figure 2. System components and experimental measuring points

Some assumptions have been made in the theoretical analysis of the system. These:

- Heat and pressure losses in system components and pipes are ignored and the system is assumed to operate under steady-state conditions.
- It is assumed that there are no kinetic and potential energy changes.
- The condensing temperature for all refrigerants is assumed to be a constant 36.5 °C (experimental data) to improve comparability. Similar usage is found in the literature [49].
- For ease of comparison, it is assumed that the compressor will maintain its isentropic efficiency at the same suction and discharge pressures.

In addition, the design parameters used in the theoretical analysis are given in Table 2.

Table 2. Design parameters used in theoretical analysis

Outdoor conditions	
Location	Sivas
Elevation	1596 m
Latitude	39
Dry bulb	-14.1 °C
Indoor conditions	
Room temp.	21 ° C
Humidity	35 %
Refrigerant Charged quantity	0.8 kg (for R410A)
Heat Pump	
Design load in heating	2.2 kW
Energy Efficiency Class	A+
- Compressor	
Type	Rotary
Capacity	2640 W
- Fan unit	
Output power	45 W

EES and experimental data (outdoor environment, temperature values at different depths, refrigerant mass circulating in the system) were used in the calculations. Ground, ambient, and outdoor temperatures were recorded during the heating season (October-March). Calculation of thermodynamic and performance parameters are given below.

Since all four components used in vapor compression heat pump cycles (Fig. 1) are in steady-flow, the cycle can be considered as a steady-flow process. The steady-flow energy equation for unit mass can be calculated as in Eq. 1.

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_{out} - h_{in} \tag{1}$$

The terms q and w are heat and work per unit mass, respectively, and h is enthalpy. *in* and *out* subscripts represent inputs and outputs, respectively. The power consumed by the compressor:

$$\dot{W}_{comp} = \dot{m}\left(h_2 - h_1\right) \tag{2}$$

Here, $\dot{m}$ mass flow rate (kg s-1), W is the electrical power (kW) consumed by the compressor to operate the system and h are the enthalpy values (kJ kg-1). Isentropic ($\eta_{comp,is}$) and volumetric ($\eta_{comp,vol}$) efficiency of the compressor:

$$\eta_{comp,is} = \frac{h_{2s} - h_1}{h_2 - h_1} \tag{3}$$

$$\eta_{comp,vol} = \frac{\dot{m}_{exp}}{\dot{m}_{the}} \tag{4}$$

Here exp and the subscripts represent experimental and theoretical data, respectively. Heat absorbed by the evaporator ($\dot{Q}_e$):

$$\dot{Q}_e = \dot{m}\left(h_4 - h_1\right) \tag{5}$$

Heat rejected by the condenser (Q_c):

$$\dot{Q}_c = \dot{m}\left(h_2 - h_3\right) \tag{6}$$

$$\dot{Q}_c = \dot{Q}_e + \dot{W}_{comp} \tag{7}$$

Pressure ratio:

$$p_{ratio} = \frac{p_2}{p_1} \tag{8}$$

Pressure difference:

$$p_{dif} = p_2 - p_1 \tag{9}$$

The energy performance of a heat pump system is defined by its COP. COP is calculated as the ratio of the evaporator heat capacity to the electricity consumed by the system.

$$COP = \frac{Q_{con}}{W_{sys}} \tag{10}$$

Also, in this study, TEWI analyzes of refrigerants, which are alternatives to R410A, were performed for the 2.2 kW GSHP system. As it is known, any system that requires energy input indirectly affects the environment with CO_2 emissions from energy production processes. TEWI simultaneously takes into account emissions caused by accidental refrigerant leaks (L_a) and electricity consumption during system operation (E_a) and TEWI is measured in kg mass units as carbon dioxide equivalent. TEWI can be calculated using the following equation [50]:

$$TEWI = \underbrace{(GWP \cdot L_a \cdot n)}_{direct\ emissions} + \underbrace{(E_a \cdot \beta \cdot n)}_{indirect\ emissions} \tag{11}$$

Here, L_a indicates leakage rate (kg) per annum, n number of years, E_a energy consumption (kWh per annum), β CO_2 emissions per kWh, $TEWI$ total equivalent warming impact (CO_2 (kg)).

3. Results and Discussion

All refrigerants included in the study were compared in detail in terms of their thermodynamic parameters and performance data, and their performance values were analyzed according to safety groups. In Fig. 3, a pressure (logarithmic) - enthalpy (*P-h*) diagram is given, considering the values obtained from the experimental data of the R410A. In Fig. 4, pressure (logarithmic) - enthalpy (*P-h*) diagram is given according to the ground temperature values (2.5 m depth) of the refrigerants according to different safety groups. In the figure, the interval 4-1 indicates the heat absorbed by the evaporator, 2-3 indicates the heat given to the environment from the condenser, and the interval 1-2 indicates the work by the compressor. The work of the compressor of a heat pump increases significantly due to the decrease in ambient temperature, which systematically affects all parameters (COP, pressure ratio, mass flow, etc.) negatively. Thermo-physical properties, safety restrictions and environmental impact are the most important factors in choosing a new refrigerant. Low viscosity in liquid and vapor phases, high specific heat, high thermal conductivity of liquid and vapor phases, high latent heat are the desired thermo-physical properties of refrigerant mixtures. Similar to the studies performed [51], it has been observed that the condensation and evaporation pressures of R32 and R410A heat pumps are quite close to each other. However, R1234yf pressure values and enthalpy range (h_4-h_1) are significantly lower like R404. The main reason for the difference here is that the mass flow rate of the refrigerant circulating in the cycle is different. In addition, although the energy consumed by the R410A and R32 refrigerants in the compressor is close to each other, the condensation enthalpy (h_2-h_1) of the R32 refrigerant is quite high except for the A2 and A3 groups.

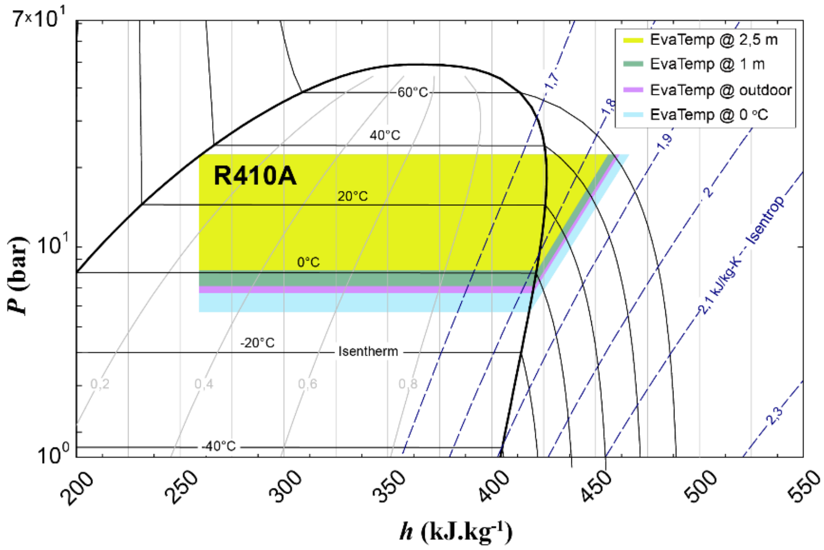


Figure 3. *P-h* diagram of experimental temperature values of R410A

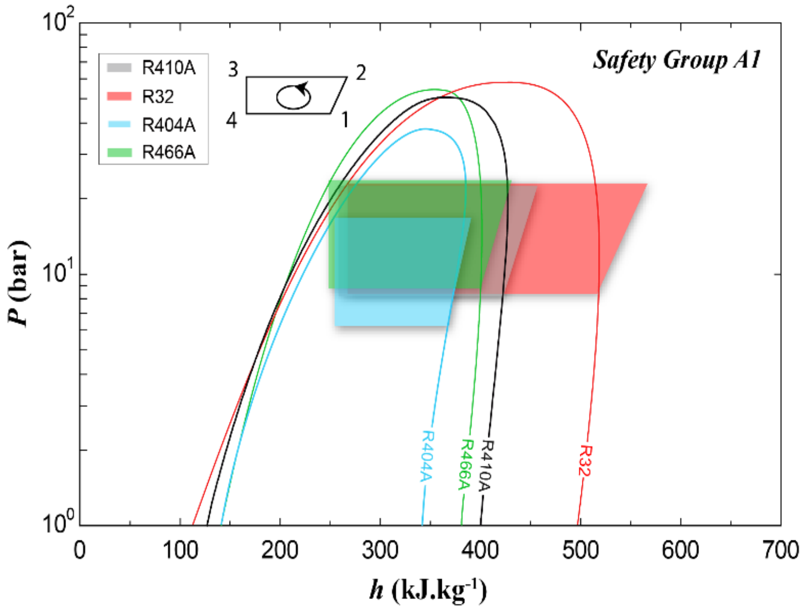


Figure 4. Comparison of P-h diagrams in experimental temperature values of refrigerants in different safety groups

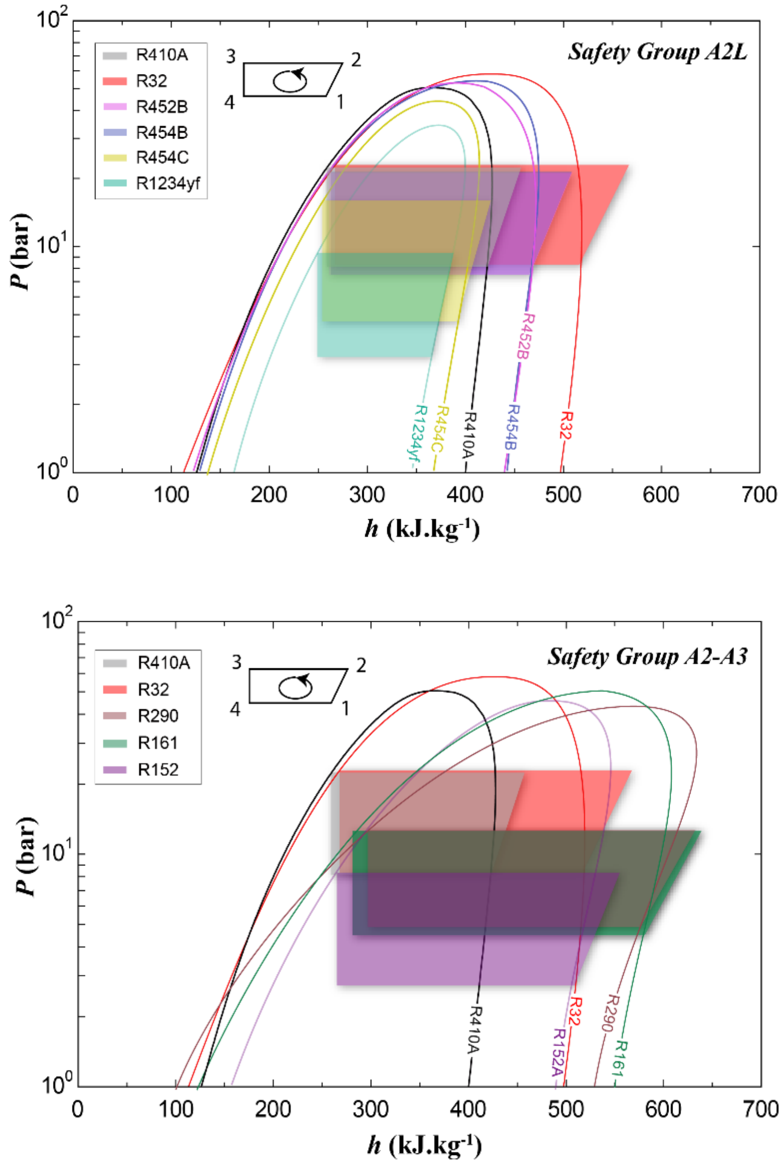


Figure 4. Comparison of P-h diagrams in experimental temperature values of refrigerants in different safety groups. ***(cont.)***

Fig. 5 shows the temperature-entropy (*T-s*) diagram of the R410A, which is prepared with reference to the experimental data. In Fig. 6, temperature-entropy (*T-s*) diagram is given according to the ground temperature values (2.5 m depth) of the refrigerants according to different safety groups. Like the P-h diagram, the interval 4-1 on the diagram refers to the heat absorbed by the evaporator, 2-3 indicates the heat given to the environment from the condenser. The range of 1-2 refers to the work by the compressor. As it is known, the capacity and efficiency of heat pumps are sensitively affected by temperature changes, decreases in temperature significantly reduce their capacity and efficiency. While the heat pump evaporation temperature values of the refrigerants in all groups are close to each other except R454C, the condensation temperature values are quite different. As stated by Çengel and Boles [52], every 1 °C decrease in the condensation temperature improves the efficiency of the system by 2%. It should not be forgotten that the capacity from the condenser is kept constant at 1.63 kW, which is the value in the experimental study. As is known, the area between the curves in *T-s* diagrams is attributed to net work. When the values of the refrigerant in the A1 and A2L groups are compared, it is seen that the values of the R32 refrigerant are quite high. In the A2 and A3 groups, although R152a and R161 refrigerants display similar properties, R152a is more successful due to less energy consumption in the compressor.

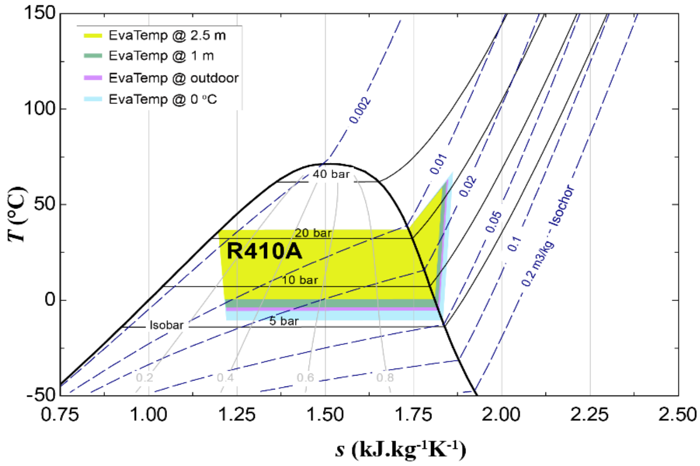


Figure 5. *T-s* diagram in experimental temperature values of R410A.

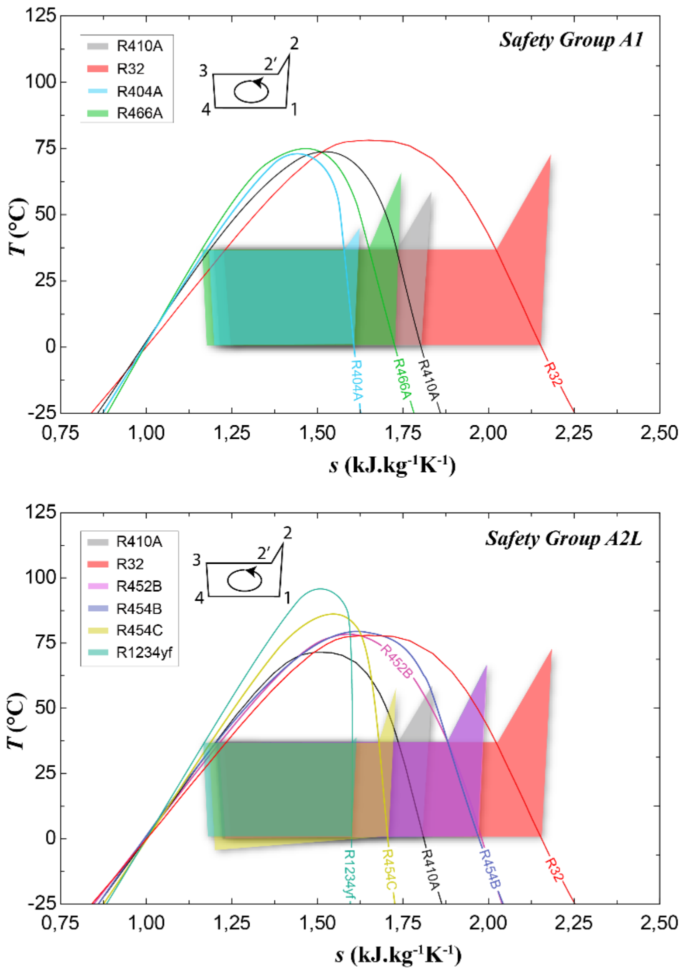


Figure 6. Comparison of T-s diagrams in experimental temperature values of refrigerants in different safety groups.

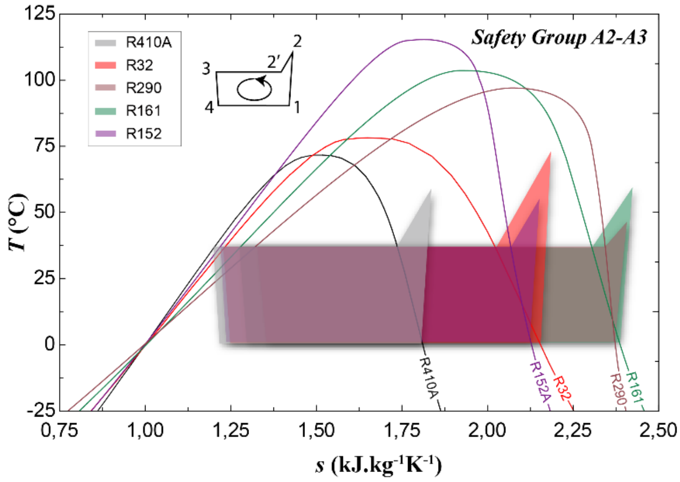


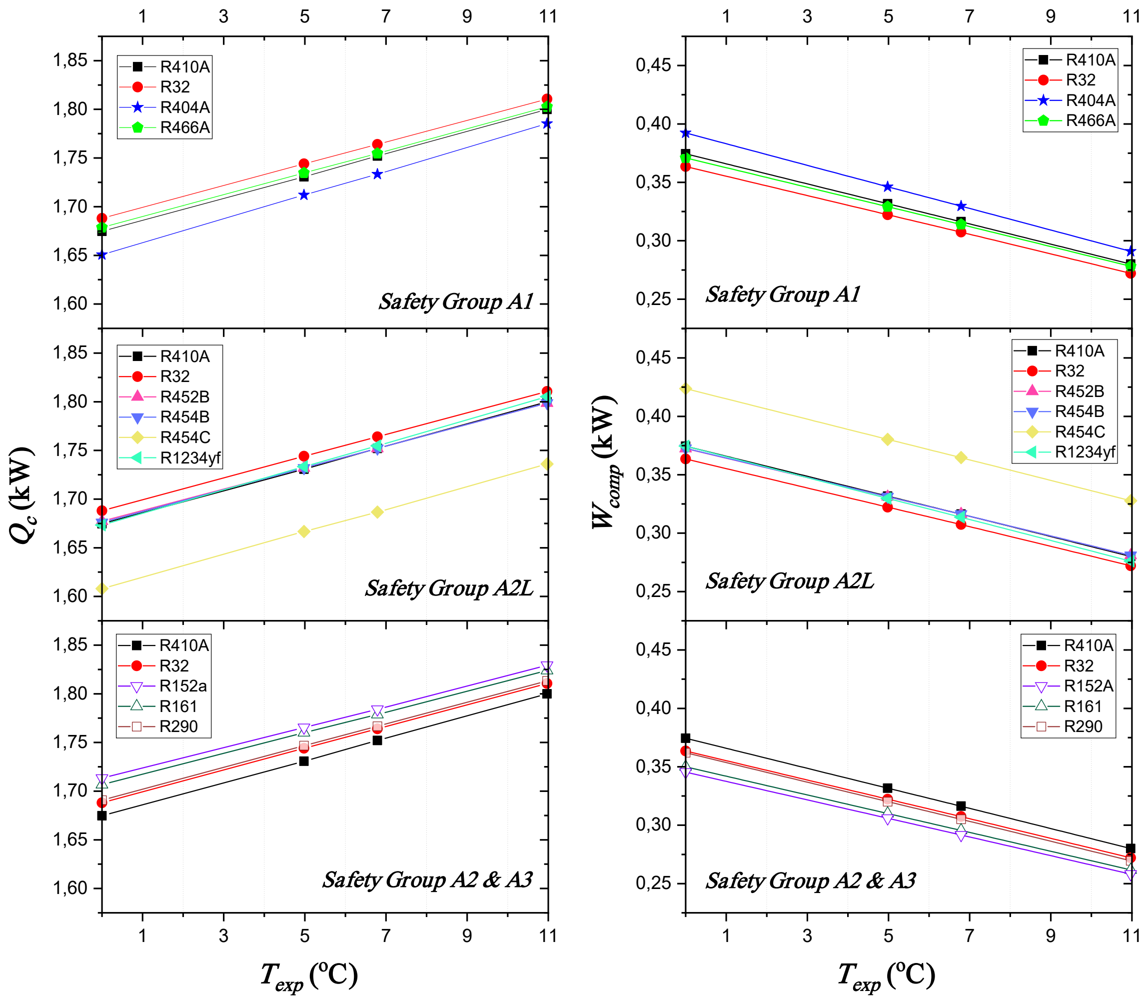
Figure 6. Comparison of T-s diagrams in experimental temperature values of refrigerants in different safety groups. ***(cont.)***

In Fig. 7, comparison of the capacity of the condenser and compressor power consumption of alternative refrigerants according to safety groups is given. Among the R410A alternative refrigerants, it can be seen that the refrigerant that reached the highest condenser capacity in A1 and A2L groups is R32. R466A in the A1 group showed a performance close to R32 (0.44% less) (Fig. 7A). Compared to other alternative refrigerants in the A1 group in terms of the power consumed by the compressor, R32 is 2.1% lower than the closest refrigerant power value (Fig. 7B). The values of R410A and R466A are very close to each other.

Increase in compressor power consumption is undesirable and adversely affects system performance. R32 refrigerant consumes 1.42% less electrical energy in the compressor than the closest value R1234yf in the A2L group. In addition, there is a significant difference between R32 and other refrigerants and R454C in both the condenser capacity (-4.3%) and the electrical energy consumed by the compressor (+17%). In the group of flammable gases (A2 and A3), the situation is slightly different from the situation mentioned above. R410A has the condenser evaporator capacity and the highest value in energy consumption in the compressor. While R290 and R32 show similar results, the highest performance was calculated in R152a with +0.5% in condenser capacity and -5% in the power consumed by the compressor, and the data are in accordance with the literature [34]. Among all safety groups and alternatives, R454C refrigerant showed the most unsuccessful results.

It was stated that the condensation temperature and capacity in the heating mode were considered constant. Accordingly, the pressure differences and ratios of the system are given in Fig. 8. Except for R404A, the pressure differences of the refrigerants in group A1 are similar and the pressure ratios are almost the same. The situation is quite different when considering refrigerants in the A2L group. Although the pressure difference of R1234yf is very low, it needs more mass flow rate to provide the required capacity (16.01 g/s @ 10.97 °C). It exhibits similar qualities with R1234yf in R454C.

The change in evaporator temperature significantly affects the COP values. Therefore, since the outdoor temperature is lower than the ground temperature, drawing heat from here during the heating season provides more success. This is the main reason why GSHP systems are more successful than air source heat pump systems. In the calculation of the COP value, the power of the circulation pump was used as approximately 0.03 kW, with reference to the experimental study results. In the analysis results, the COP value of the system has shown 30% more performance when the temperature value is 10.97 °C (2.5 m depth) compared to an outdoor environment at 0 °C (Fig. 9A). The refrigerant used in the heat pump unit affects the COP performance. As the evaporation temperature increases, the compression pressure ratio of the refrigerant decreases, so the power consumed by the compressor decreases in parallel with the enthalpy difference (h_2-h_1). It is seen that the best alternative to R410A in A1 and A2L group is R32. According to the 2.5 m ground temperature value (10.97 °C), the R32 refrigerant has increased the COP value by 3.1% compared to R410A, and this difference has increased up to 7.1% with R404A. The results are consistent with the studies performed [22]. R454C in the A2L group is the refrigerant with the worst COP value. In the A2 and A3 groups, the highest COP values were obtained in R152a. Similarly, the COP values of other refrigerants in the group are higher than R32 and R4010A. The COP differences of the refrigerants in this group from R410A vary between 4.1% (R290) - 8.5% (R152a). The average COP value of the system, on which the experimental parameters are referenced [47], is shown in Fig. 9A. There is a 3.5% difference between the experimental results and this study. This difference is consistent when neglected losses are taken into account.



A **B**

Figure 7. A. Condenser capacity of alternative refrigerants according to safety groups, B**.** Compressor power consumption of alternative refrigerants according to safety groups

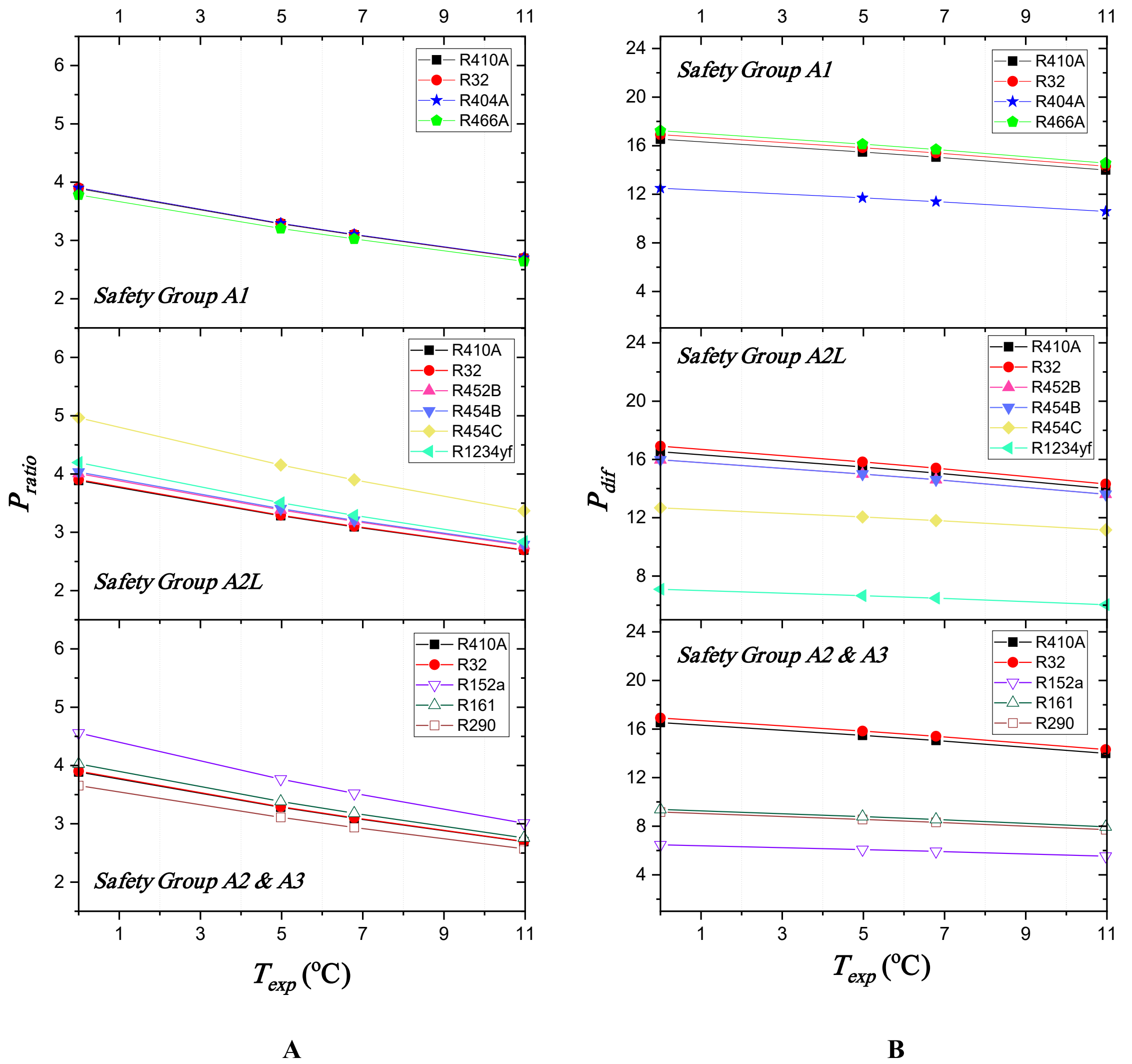
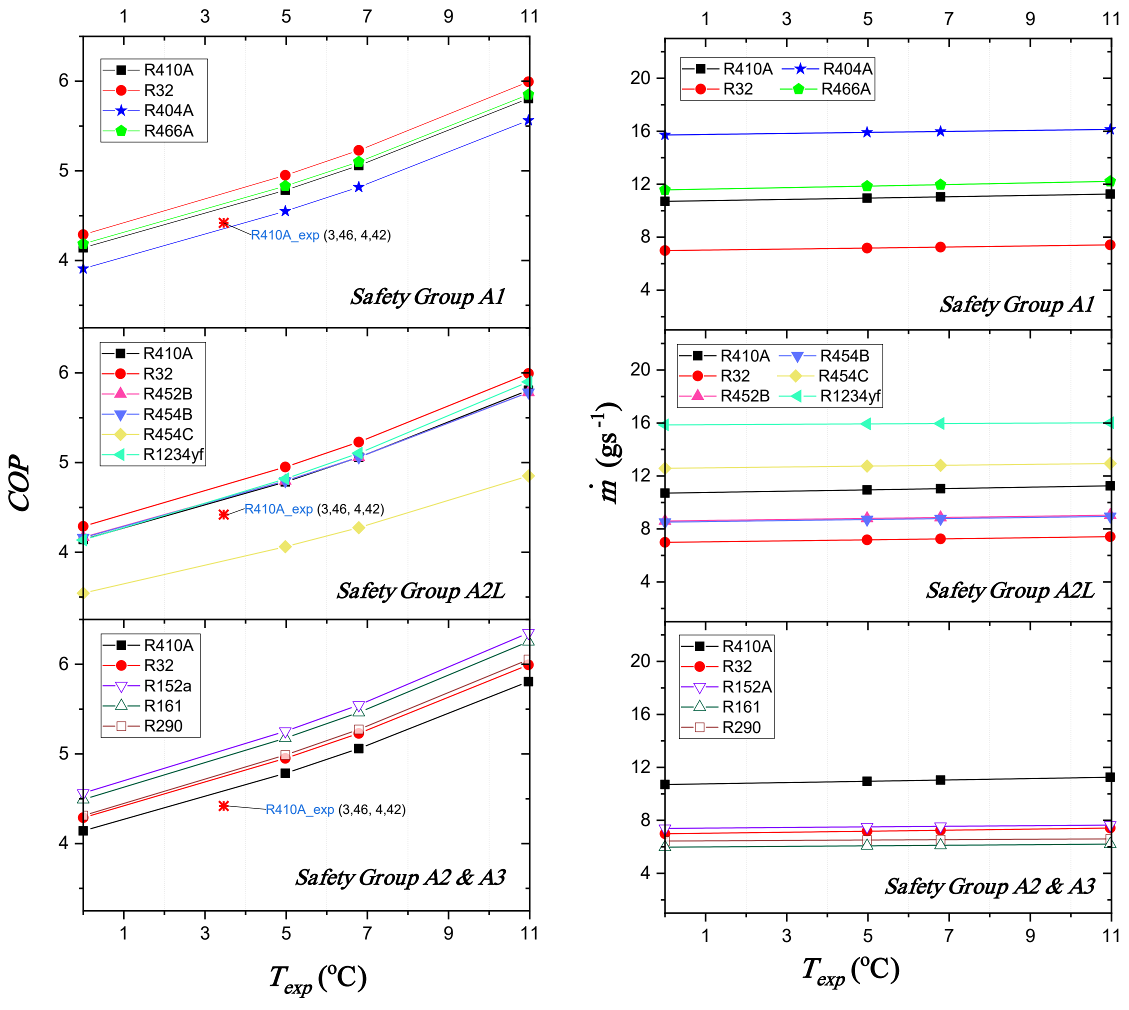


Figure 8. A. Pressure ratio of alternative refrigerants according to safety groups. B. Pressure differences of alternative refrigerants according to safety groups

The mass flow rate values of the refrigerant that must circulate in the heat pump system depending on the evaporation temperature are given in Fig. 9B. In A1 and A2L group refrigerants, the lowest mass flow rate belongs to R32. On the other hand, R404A and R454C have the highest values in terms of mass flow rate and the lowest values in terms of COP value. This situation is also an indication of the inadequate performance of these refrigerants. Although R1234yf performs similarly to R410A in terms of COP value, it has the highest value in the first two groups in terms of mass flow rate. The mass flow rates of refrigerants in groups A2 and A3 are very close to each other.



A **B**

Figure 9. A. COP values of alternative refrigerants according to safety groups, B. Mass flow rates of alternative refrigerants according to safety groups.

In the refrigerant selection process, environmental measurements are often used alongside applicability. The most widely used of these measurements are GWP and Total equivalent warming impact (TEWI) values [53]. TEWI considers the CO_2 emissions of the systems into the atmosphere by taking into account their direct (leakage emissions) and indirect (emissions produced by the energy consumed during the operation of the system) effects [54] and TEWI is recommended as a comparative index of global warming effects for different options for a given application [55].

In Fig. 10, TEWI analysis results are given for the above-mentioned system, taking into account the ground temperature change and the mass of R410A refrigerant supplied to the system during the experiments. The masses of the alternative refrigerants to be given to the system were calculated according to the density values given in Tab. 1, taking the volume of the system as a reference. The CO_2 emission value per kWh from electricity consumption is taken as 255 g CO_2/kWh for the European region from the European Environment Agency tables [56]. The annual leakage amount of the system is taken as 4% [50]. The use of R32 instead of R410A according to the 2.5 m ground temperature value reduced the CO_2 emission by 2.54% (72.5 kg) and this reduction rate increased up to 7.06% (201 kg) in R152A. At 0 °C, this reduction value reached up to 2.67% (99.14 kg) for R32.

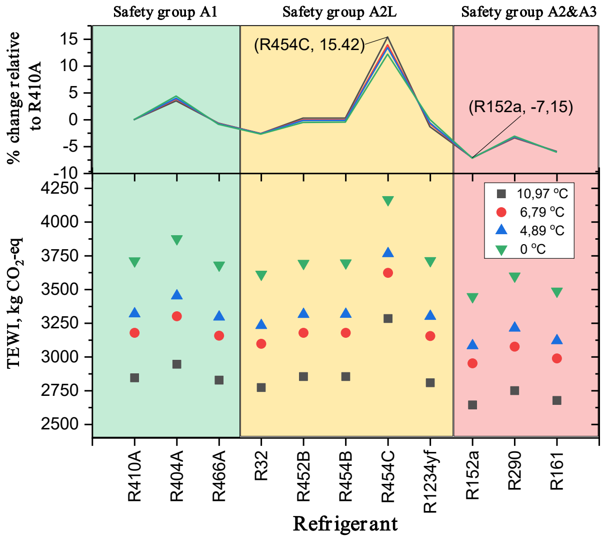


Figure 10. TEWI value of alternative refrigerants according to safety groups

Considering 1800 hours of operation for the heating season (October-March), the annual electricity consumption according to the temperature value at 2.5 m ground depth is shown in Fig. 11 from low to high. R454C provided the highest electricity consumption at all temperature values. Compared to R410A, this value is approximately 17% higher. The lowest electricity consumption was in A2 and A3 groups. The most successful refrigerant in the A2L group was R32. R32 saved 2.85% in total electricity consumption during the heating season compared to R410A. As the evaporation temperature decreased, the electrical energy consumed by the compressor varied depending on the mass flow rate. For example, at 10.97 °C, R1234yf consumed less electrical energy compared to R410A, while at 0 °C it consumed more energy.

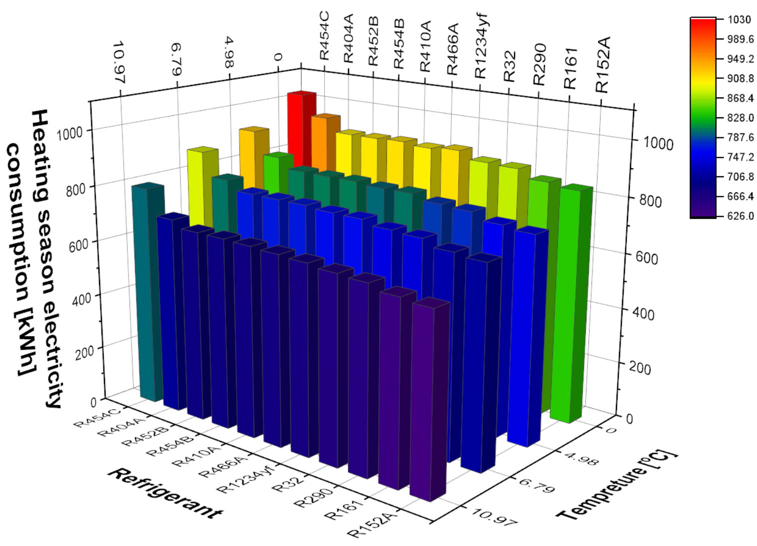


Figure 11. Electricity consumption values of the GSHP system according to the type of refrigerant depending on the temperature value in the heating season

4. Conclusion

In this study, the effect of alternative refrigerants instead of R410A in a GSHP system was investigated theoretically by referring to experimental data. Except for R404A refrigerant, which is included in the comparison to see the effect of conventional refrigerants within the scope of the study, the GWP value of all other refrigerants is below the limit of 750 by the European F-Gas Regulation (Regulation (EU) No 517/2014) [13]. It can be challenging by both manufacturers and service providers, as there are too many alternative refrigerants below this GWP value. It is also quite confusing by the end user. Therefore, it is very important to choose the best alternative in terms of environmental, economic and energy carrying capacity. In addition, every factor that will increase the performance parameters of GSHP systems, which are already quite successful, without changing / reducing the cost, is very important in terms of the widespread use of these systems. In this context, some of the important results obtained from the study can be listed as follows:

- In the amount of refrigerant circulating in the system, approximately 35% is saved with R32 compared to R410A refrigerant. While this ratio provides an economic advantage with the amount of refrigerant used, it significantly reduces the amount of refrigerant that will be released into the environment in case of possible system leaks. Although it does not pose a problem due to its similar properties in both refrigerants in terms of ozone depletion capacity, it provides a serious gain potential in terms of GWP value.
- Refrigerants in the A2 and A3 groups are the most successful for COP and operating cost. Especially R152a, which is in the flammable fluid class (A2), provided the most successful results in the study. R152a provided a 10% increase in COP compared to R410A. However, it should be kept in mind that it is subject to restrictions due to its flammability capacity.
- Among the refrigerants in the A1 and A2L groups, the most successful results were achieved with the R32. This refrigerant achieved the highest performance in terms of compliance with the F-gas regulation and its low mass flow rate requirement, COP value and operating cost after A2 and A3 groups. However, it is stated by Federation of Environmental Trade Associations that replacing systems using R410A directly with R32 would void the warranty terms and could pose security risks [57].
- Apart from R32, refrigerants (R452B, R454B, R454C) classified by the EPA as being used in residential and commercial conditioning systems were higher than R410 in terms of operating costs. In addition, R454C was determined to have the lowest values in all respects in the study.
- The use of R32 refrigerant instead of R410A contributes to the reduction of CO_2 emissions.
- With the decrease in the evaporation temperature, fluids with high mass flow rate start to consume more electrical energy.

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Nomenclature

Symbols		**Subscripts**	
$\dot{m}$	mass flow rate, kg/s	*a*	annum
COP	coefficient of performance	*c*	condenser
EPA	environmental protection agency	*comp*	compressor
E	energy consumption, kWh	*dif*	difference
GSHP	ground source heap pump	*e*	evaporator
GWP	global warming potential	*exp*	experimental
h	specific enthalpy, kJ/kg	*ghe*	ground heat exchanger
HFC	hydrofluorocarbon	*h*	heating
Q	heat capacity, kW	*in*	Inlet
q	heat per unit mass, kJ/kg	*is*	Isentropic
W	rate of work or power, kW	*out*	outlet
w	work per unit mass, kJ/kg	*R*	refrigerant
L	leakage rate, kg	*the*	theoretical
LFL	lower flammability limit, kg/m^3	*vol*	volumetric
n	life of the system		
η	efficiency		
P	pressure, kPa		
s	specific entropy, kJ/kgK		
T	temperature, K or ◦C		
TEWI	total equivalent warming impact		
u	specific internal energy, kJ/kg		
v	specific volume m$^{3/}$kg		
β	CO_2 emissions per kWh		