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Reducing Energy Demand in Liquefied Petroleum Gas Evaporation Processes

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1. Introduction

Gaseous fuel remains a tremendously significant part of the traditional economy. Gas consumption can sufficiently satisfy many municipal, domestic, technological and industrial needs. Currently, this type of energy carrier can be divided into a group of natural and liquefied gases. Natural gas is traditionally a mixture of vapors and gases containing predominant amounts of methane (71–98%, for groups LS–E). Liquefied gas, however, contains primarily hydrocarbon compounds like propane and butane, the mixture of which is typically stored under pressure, usually in liquid form. Natural gas is typically used in areas with gas networks. On the other hand, in areas without access to this type of medium, it is possible to use liquid gas. Regardless of how the gas is stored, this type of energy carrier is considered as an environmentally-friendly, because it allows for the reduction of greenhouse gases, including CO_2 (Ekorynek.com 2018). In addition, there are no sulfur dioxide emissions during combustion, as it is with coal, coke and oil. For these energy carriers, gaseous fuels have significantly lowered emissions of nitrogen dioxide, carbon monoxide and PM10 particulate matter. Much attention has been paid to aspects related to the emission of pollutant in literature. Jerzak (Jerzak 2014) properly analyzed the effect of the CO_2 injection distance on the emissions of NO_X and CO during the combustion of natural gas in air enriched with oxygen up to 25%. Pathak et al. (Pathak et al. 2017) discussed the use of solar energy through seamless integration with existing heat source for a few processes involved in automobile industries. Wójcik et al. (Wójcik et al. 2017) presented an innovative mathematical model for the distribution of emissions from vehicles. Noch et al. (Noch et al. 2018) analyzed the emission of pollution to the atmosphere during the thermal energy production. Piątkowski and

Bohdal (Piątkowski & Bohdal 2011) investigated the influence of ecological properties of a spark-ignition engine powered by a propane-butane mixture.

It is also worth noting that gas is mainly used by various companies that care about sustainable development. This raw material is becoming increasingly popular due to the current limits of emission of pollution and penalties for exceeding them. The use of gas as an ecological fuel intentionally allows industrial plants to meet the requirements of specific regulations and concurrently to create an image of a socially responsible organization. In addition, it additionally allows for a significant reduction in the operating costs of heating systems. Modern gas appliances enable easy regulation and automation of the combustion process, which allows to obtain a high-energy effectiveness and uniform combustion parameters. Industrial plants often use a lot of energy. Its production with the use of conventional fuels (coal, coke, fuel oil) may have a negative impact not only on the environment, but also on the health of employees. This is a further argument in favor of replacing them with a gaseous fuel (Eko-rynek.com 2018).

2. Literature review

A standard form of using gaseous fuel is to deliver it via a gas distribution network (Englart et al. 2019). However, it is also possible to use liquid gas in its liquefied form. It is a product of a different kind than traditional fuels. At European level, it has been recognized as an alternative fuel and as a low-carbon, accessible and efficient energy carrier. The use of LPG should be promoted in order to ensure better air quality in Poland. It is also recommended to use this energy source more for heating purposes (POGP 2019). Liquefied form allows for storing large amounts of gas in smaller storage tanks, while allowing for its free transport. In the literature there are many possible solutions based on the practical use of liquefied gaseous fuel. Williams and Larson (Williams & Larson 2003) compared different direct and indirect liquefaction technologies for making fluid fuels from coal. Zakaria and Mustafa (Zakaria & Mustafa 2011) presented LPG characteristics in the cylinder during the exhaust process via modification of the existing composition design. Qeshta et al. (Qeshta et al. 2015) analyzed the effect of LPG sweetening process using tertiary alkanolamine. Barrera et al. (Barrera et al. 2012) performed the experimental analysis using absorption refrigeration advanced Solar cooperated with Generator Absorber eXchanger system. Dai et al. (Dai et al. 2018) presented a detailed investigation of an air-source liquefied petroleum gas – solar driven absorption heat pump using also Generator Absorber heat eXchanger. Shi (Shi 2012) presented an original model for the proper selection of LPG vaporization stations for storage tanks. Dolna and Mikielewicz (Dolna & Mikielewicz 2017) presented the numerical research on the ground coupled compressor heat pump operates under quasi-steady mode. The authors analyzed the direct influence of a single field type vertical ground heat exchanger on the surrounding ground. Shi et al. (Shi et al. 2008) described a novel LPG gas supply system utilizing solar thermal energy. This authors system manages hot water produced by a solar water heating system as vaporization heat source and uses an electric heater as assisted heat source. Żuchowicki and Żuchowicki (Żuchowicki & Żuchowicki 2009) presented the selected problems of the gas systems reliability operation. Shi et al. (Shi et al. 2018) presented the transient behaviors of liquefied petroleum gas (LPG) natural vaporization in a cylinder using an experimentally validated model. Shi et al. (Shi et al. 2019) investigated a new LPG vaporization system utilizing direct-expansion solar-assisted heat pump for residential gas supply. In another paper, these authors (Shi et al. 2019) focused on the advancements and the current status of this system (DX-SAHPs). Han et al. (Han et al. 2017) performed thermal design optimization analysis for intermediate fluid vaporizer using liquefied natural gas. Shi et al. (Shi et al. 2019) claimed that integrating solar collector-evaporators with some modern technologies, such as photovoltaic, phase change material thermal storage and heat pipe, makes DX-SAHPs perform better under different climates and applications. Suslov et al. (Suslov et al. 2015) described an experimental heat pump unit for water thermal preparation in the closed water supply units.

This paper focuses on the more efficient use of renewable energy sources in the LPG vaporizer systems in moderate climate conditions. This process is typically used when the natural evaporation of gas in the storage tank is insufficient in relation to its demand. The use of such systems enables more efficient use of a low-emission and efficient energy carrier to supply gas systems with relatively high gas demand.

3. Operating principle of LPG vaporizer

The following method is commonly used to evaporate LPG: the gas in the liquid phase is supplied to the vaporizer, which raises its temperature and heats up the liquid phase above the boiling point at the discharge pressure. The liquefied gas is evaporated by indirect heating using hot water at a temperature from 40 to 85°C. (Pathak et al. 2017, Kowalczyk 2004). To ensure the precise interpretation of this process, the temperature range is shown in the diagram as evaporation temperature curves for propane, butane and their mixtures (Fig. 1). It is also worth noticing that the temperature range is directly related to the pressure range in the system components (tank, vaporizer, etc.). For example, the maximum overpressure in the above-ground storage tanks is 16 bar.

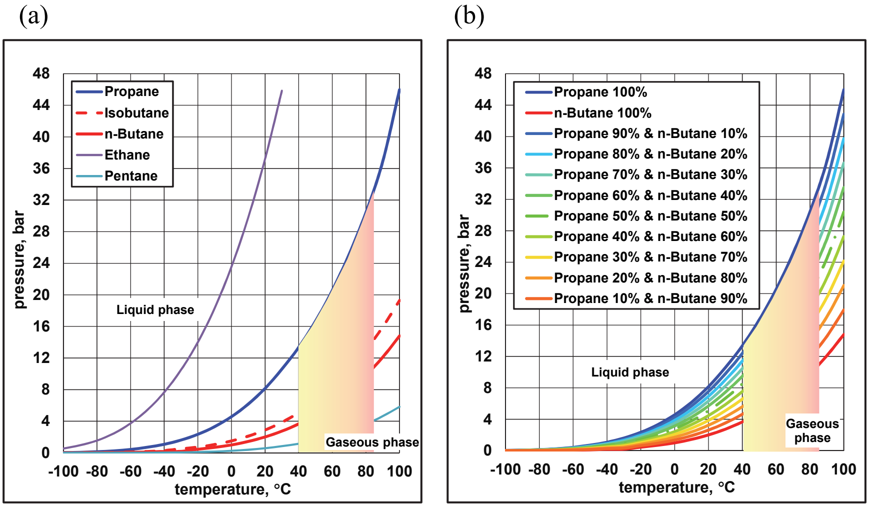

Fig. 1. Vapor pressure of selected Liquefied Petroleum Gases (Zajda & Tymiński 1999): (a) Propane, n-Butane and Isobutane, (b) mixtures of Propane and n-Butane

Depending on the method and the type of supply of the receivers, vaporizers are divided into two types: Feed-Back and Feed-Out. The first operates on the principle of gas-phase transmission through the vaporizer to the storage tank from where the gas is supplied to the gas system and the receiver. In the Feed-Out system, the gas from the vaporizer flows directly to the system and the receiver. The main advantage of the Feed-Back system is that it eliminates the direct consumption of gas in its liquid phase by the system by redirecting the gas from the vaporizer back to the gas storage tank. Also, the liquefied gas evaporation in the storage tank can be used to the maximum in this system. In Poland's climatic conditions, the Feed-Back system seems to be economically unjustified. At low outdoor temperatures, there will be large heat losses in the storage tank causing increased energy demand for gas heating. In Polish climatic conditions, the use of vaporizers in the Feed-Out system is recommended.

4. Requirements for the operating configuration of LPG vaporizers

Standard LPG systems provide an adequate amount of gas from natural evaporation through heat extraction from the wetted surface of the storage tank. Shi and others discussed a detailed description of the process of natural evaporation of gaseous fuel (Shi et al. 2018). The authors also pointed out the appropriate adjustment of the number of storage tanks to the liquid gas system. In their opinion, in the case of many storage tanks, a system with liquid phase consumption and forced gas evaporation in the evaporator should be designed. This variant allows for a reduction the storage area of tanks. In addition to the technical factors, economic factors should also be considered (Shi et al. 2012). For this reason, electrical and water equipment solutions are available on the market. The first of them is typically used in systems with a lower power output and performance not exceeding 200 kg/h. Water devices are used in systems with a performance greater than 200 kg/h and whenever it is not possible to provide sufficient electrical power to supply the electrical vaporizer.

The vaporizers can be combined in a parallel arrangement. However, the fewer vaporizers work in a single battery, the easier it is to achieve a stable operation and the possibility of adjusting individual system parameters. For many industrial plants where there is no possibility of gas supply interruptions (e.g. glass factories, poultry farms) a more efficient solution is to use two smaller LPG vaporizers with less power than one more powerful vaporizer. Therefore, it is possible to use the power reserve to guarantee reliable operation of the system in case of a failure, malfunction or defect of the second vaporizer. The condition for proper operation of a system consisting of several vaporizers represents the selection of devices with the same power or effectiveness. Another necessary condition for the devices of this type working in a one system is to maintain the symmetry of the position of supply collectors and consumption of gas after the vaporizers. Moreover, the performance of vaporizer (in kg/h) should be 20-30% higher than the capacity of the receiver. The approx. 30% reserve guarantees more stable operation of both electric and water vaporizers and also is a safe reserve of energy in case of a sudden and unexpected high gas consumption, e.g. during the system start-up (Gasconcept Kurpińscy 2019).

5. Vaporizer supply options

Based on the analysis of vaporizer supply systems operation, solutions based on a conventional energy source (CES) were proposed. Vaporization of gaseous fuel taken from the gas storage tank takes place in a vaporizer supplied by a traditional high-temperature gas boiler (GB) (Fig. 2 (a)). This energy source can be replaced by a low-temperature gas boiler or a more efficient low-temperature condensing boiler or by a gas absorption heat pump (Fig 2 (b)). In this way, a system based on renewable energy source (RES) such as Ground Air Heat Exchanger (GAHE), Horizontal Heat Exchanger (HHE) or a Vertical Heat Exchanger (VHE) can be created (Fig. 2 (b)–(e)). Moreover, a solution using two cooperating lower heat sources (outside air and ground) allows creating a Multi-RES system (Fig. 2 (b)+(c)). The proposed solutions should be based on a vaporizer with an adequately larger heat exchange area and a design that ensures effective heating and effective gas evaporation.

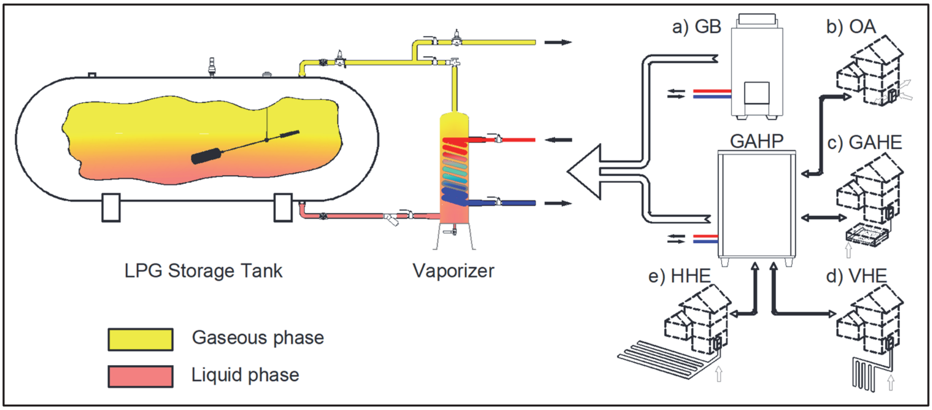

Fig. 2. Diagrams of considered gas vaporization systems equipped with: conventional energy source (a) GB, renewable energy sources: GAHP assisted by: (b) OA, (c) GAHE, (d) HHE, (e) VHE, (Abbreviations: GB – Gas Boiler, GAHP – Gas Absorption Heat Pump, GAHE – Ground Air Heat Exchanger, HHE – Horizontal Heat Exchanger, OA – Outdoor Air, VHE – Vertical Heat Exchanger)

6. Calculation results

The analysis was prepared as a variant for liquid gas evaporation systems using a vaporizer with a calculated performance 200 kg/h, which was supplied by the particular devices shown in Fig. 2. In the considerations, the parameters of the actual devices using only gaseous fuel were used, discussed in detail in the previous chapter. It was assumed that the tank is filled with propane, for which it was also assumed that it is necessary to heat the liquid phase in the vaporizer at outdoor air temperatures lower than 6°C. Because of the heat losses at low outdoor air temperature, it was assumed that the gas phase is heated to 20°C.

The calculations assume two modes of all-year-round operation:

- constant effectiveness for industrial applications,
- variable effectiveness for domestic needs (preparation of meals, heating and domestic hot water preparation).

The gas utilization effectiveness is expressed as the ratio of the heating performance of a whole device to the heat taken from the gas burner (calorific value of the gas). Fig. 3 shows the relation between the device's effectiveness for various system operating temperatures and outdoor air temperature for the considered types of gas devices cooperating with the vaporizer. In the analysis of all-year-round operation, the average times of occurrence of particular outdoor air temperatures at averaged relative air humidity for the city of Wrocław were also used (Fig. 4). Next, the operation of gas vaporization systems for various assumed operation parameters (gas boiler, gas condensing boiler, absorption heat pump using energy from outdoor air or the ground – heat exchanger in three configurations: air and a system of horizontal and vertical heat exchangers) was compared (Fig. 2).

The following formula (1) was used to determine the annual gas consumption of individual devices $\dot{V}_a$ (m^3/h):

$$\dot{V}_a = \sum_{i=1}^{n} \frac{\tau_i \left[Q_V\left(t_o\right) + Q_P\left(t_o\right) \right] v_g}{\varepsilon_i\left(t_o\right)} \tag{1}$$

where:

$\varepsilon_i(t_o)$ – effectiveness of the device under outdoor air temperature conditions (according to Fig. 3); dimensionless,
τ_i – time of occurrence the outdoor air temperature (acc. to Fig. 4); h,
$Q_P(t_o)$ – heat of gas preheating at outdoor air temperature conditions; W,
$Q_V(t_o)$ – heat of gas vaporization at outdoor air temperature conditions; W,
ν_g – specific gas consumption coefficient; m^3/(h·W).

Heat of gas vaporization (2) can be expressed as follows:

$$Q_V\left(t_o\right) = \dot{m}_g \left[h_{Lp}\left(t_o\right) - h_{Gp}\left(t_o\right) \right] \tag{2}$$

where:

$\dot{m}_g$ – gas mass flow rate; kg/s,
$h_{Lp}(t_o)$ – specific enthalpy of liquid phase; J/(kg·K),
$h_{Gp}(t_o)$ – specific enthalpy of gaseous phase; J/(kg·K).

Heat of gas preheating (3) can be calculated as:

$$Q_P\left(t_o\right) = \dot{m}_g \left[h_{Gp}\left(20°\mathrm{C}\right) - h_{Gp}\left(t_o\right) \right] \tag{3}$$

where:

$\dot{m}_g$ – gas mass flow rate; kg/s,
$h_{Gp}(20°C)$ – specific enthalpy of gaseous phase at an outdoor air temperature of 20°C; J/(kg·K),
$h_{Gp}(t_o)$ – specific enthalpy of gaseous phase; J/(kg·K).

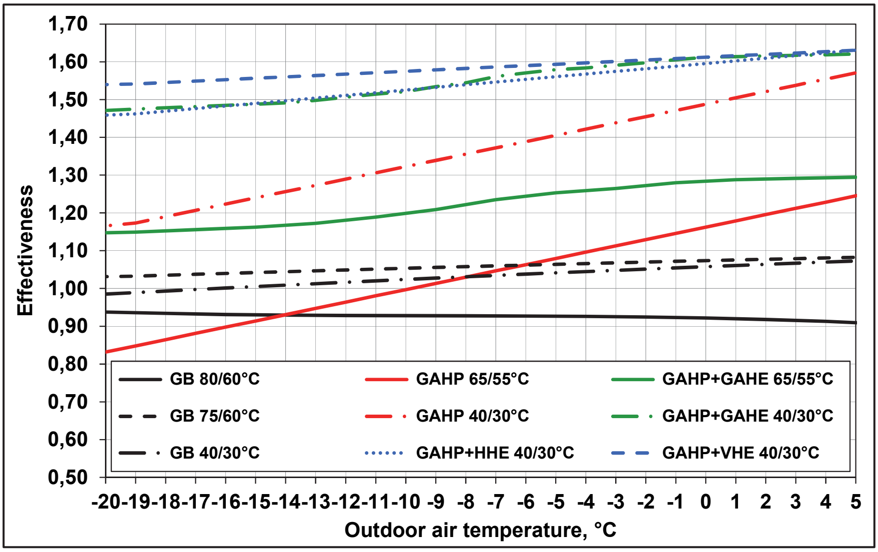

Fig. 3. Effectiveness of the considered gas vaporization systems expressed as a function of the outdoor air temperature, (Abbreviations: GB – Gas Boiler, GAHP – Gas Absorption Heat Pump, GAHE – Ground Air Heat Exchanger, HHE – Horizontal Heat Exchanger, OA – Outdoor Air, VHE – Vertical Heat Exchanger)

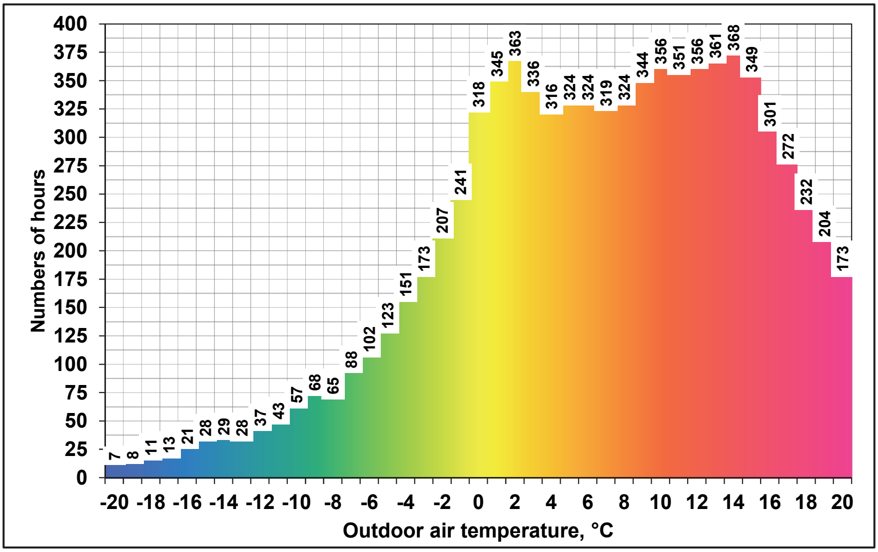

Fig. 4. Annual number of hours of occurrence of outdoor air temperature

It can be seen in Fig. 3 a simple replacement of the conventional energy source (gas boiler) with a condensing appliance increases the effectiveness of the entire system (from 0.90 to 1.10). Moreover, it is worth noting that the use of each of the renewable energy sources allows a noticeable increase in the effectiveness of the whole system (from 0.90 to 1.60).

Fig. 5 shows the results of a comparative analysis of the considered gas supply systems. The analysis was carried out in relation to a system based on a conventional gas boiler operating at standard parameters (80/60°C).

As can be seen, the use of proposed systems: GB (condensing boiler), GAHP or GAHP with GAHE, VHE or HHE can result in energy savings in gas consumption (from 14% to 42% per year, depending on the profile of gas consumption).

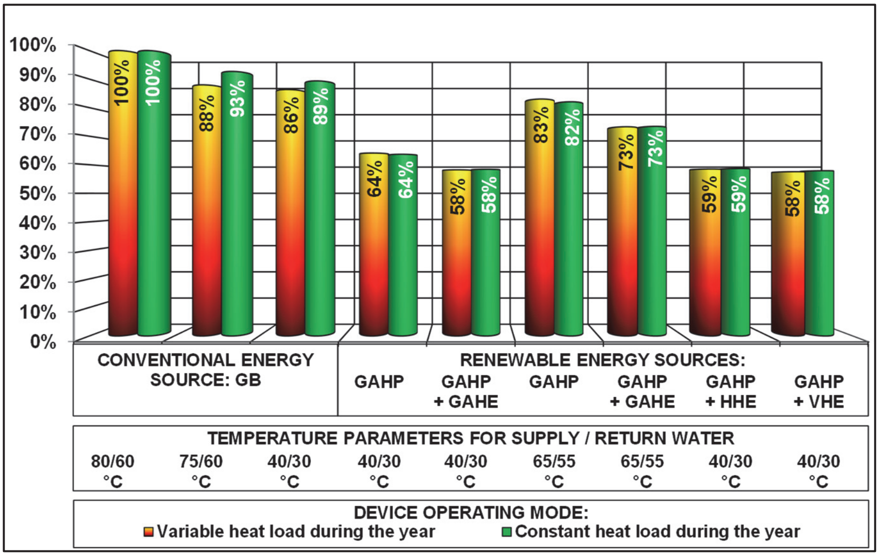

Fig. 5. Comparison of percentage gas demand of considered gas vaporization systems with respect to the conventional energy source (gas boiler operating under temperature parameters 80/60°C)

In terms of purchasing costs, the most effective solution is to use a condensing boiler operating at low temperature conditions (40/30°C), where gas consumption can be reduced by up to 14%. Otherwise, in the context of the gas demand, the most economic system is GAHP, which can work with GAHE with VHE or HHE. In this case, it is possible to reduce gas consumption by up to 42%.

7. Conclusions

In comparison to the classic and currently commonly used systems, the alternative solutions based on modern gas devices and renewable energy presented in the paper, show considerable potential for energy savings in liquid gas evaporation systems for the gas supply to various facilities.

The analysis of energy generation using low-temperature gas boilers, gas absorption heat pumps and heat pumps with combination with various lower heat sources convinces the advisability of undertaking the subject of research.

It has been demonstrated that the proposed solutions can significantly reduce the energy consumption for the evaporation of liquefied petroleum gas in an environmentally friendly way by exploiting the energy potential of its natural resources.

In addition, gas absorption heat pumps can be used to efficiently produce coolant for both production and social needs (e.g. for cooling of offices) during the summer when natural evaporation is sufficient and there is no need to start up the vaporizer. This allows for the purchase of smaller cooling devices and the reduction of electricity demand during warm periods throughout the year.

The analysis leads to the following conclusions:

- replacing the traditional gas boiler with a low-temperature gas boiler working with a larger heat exchanger (larger heat exchange area and higher heating power) allows reducing the energy demand from 7% to 14%,
- it is possible to reduce gas consumption to 36% by using gas heat pumps in comparison to the conventional energy sources,
- expansion of the heat pump system with ground heat exchanger, vertical or horizontal heat exchangers allows for gas savings of up to 42%,
- the analyses confirm the need for further research on other solutions based on renewable energy sources to achieve greater energy savings.

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Abstract

The paper discusses the use of renewable energy sources for the LPG vaporizer systems in a moderate climate. The presented alternative solutions based on modern gas devices and renewable energy show great potential for energy savings in liquid gas evaporation systems in comparison to classical and currently commonly used systems. It has been demonstrated that the proposed solutions can significantly reduce the consumption of energy used to evaporate LPG in an environmentally friendly manner. The use of gas heat pumps in relation to a traditional energy source enables gas consumption to be reduced to 36%. The extension of the heat pump system with ground air heat exchanger or with vertical or horizontal heat exchangers, allows savings in gas consumption up to 42%. Moreover, the application of such systems enables more effective use of low emission and efficient heating medium in gas systems. In addition, in summer, when there is no need to evaporate the liquefied gas, these devices can be used to cold-production for, social and living needs.

Keywords:
energy savings, LPG, vaporization technologies, heat pump, renewable energy

Obniżenie zapotrzebowania na energię w procesach odparowania skroplonego gazu

Streszczenie

W artykule omówiono wykorzystanie odnawialnych źródeł energii w układach parowników LPG w klimacie umiarkowanym. Przedstawione alternatywne rozwiązania oparte na nowoczesnych urządzeniach gazowych i energii odnawialnej wykazują duży potencjał oszczędności energii w instalacjach odparowania gazu płynnego w porównaniu z klasycznymi i obecnie powszechnie stosowanymi systemami. Wykazano, że proponowane rozwiązania mogą znacząco ograniczyć zużycie energii wykorzystywanej do odparowania LPG w sposób przyjazny dla środowiska. Zastosowanie gazowych pomp ciepła w stosunku do tradycyjnego źródła energii pozwala na redukcję zużycia gazu do 36%. Rozbudowa systemu pomp ciepła o pojedynczy gruntowy powietrzny wymiennik ciepła lub dodatkowo współpracujący z pionowymi, lub poziomymi systemami odwiertów umożliwia uzyskanie oszczędności zużycia gazu sięgających nawet 42%. Ponadto zastosowanie takich systemów pozwala na bardziej efektywne wykorzystanie niskoemisyjnego i wydajniejszego czynnika grzewczego w systemach gazowych. Ponadto w okresie letnim, kiedy nie ma potrzeby odparowywania skroplonego gazu, urządzenia te mogą być wykorzystywane do produkcji „chłodu” przeznaczonego na potrzeby społeczne oraz bytowe.

Słowa kluczowe:
oszczędność energii, LPG, technologie odparowania, pompa ciepła, energia odnawialna