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Benefits and reliability of air-to-water heat pumps in residential applications, using R-290 refrigerant and an alternative design solution to guarantee high safety with standard components.

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Abstract

The optimisation of energy consumption, the search for higher system efficiency and the need to reduce CO_2 emissions are driving the heat pump market, especially in residential applications. In EMEA especially, the need to switch to alternative refrigerants is changing the criteria for selecting components and developing projects. Most of the market trends have already identified flammable refrigerants as the way to solve compliance issues, while at the same time raising new issues regarding usability and reliability of potentially explosive devices in residential systems. Unit and component manufacturers are starting to work together in order to develop affordable and reliable solutions, not only improving component technologies and their mounting in the unit, but working closely together right from the start of the project.
Here below we describe an example of a fruitful collaboration for the development of an R-290 air-to-water heat pump, where accurate unit design, experience as HVAC component and heat pump manufacturers, have led to the development of a product with the highest performance in terms of efficiency and reliability, meeting all the standards for the use of flammable refrigerants on the European residential heating market.

Keywords: heat pumps; R-290; safety; DC; EEV;efficiency

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1. Introduction

The Kigali amendment to the Montreal Protocol [1] entered into force on 1 January 2019, and was aimed at phasing down hydrofluorocarbons (HFCs) by cutting their production and consumption, so as to reduce so-called direct CO_2 emissions. However, actions to reduce the use of HFC refrigerants had already started in most developed countries. In the European Union, F-gas regulations [2] were published in 2014, establishing restrictions to the use of HFC refrigerants according to their global warming potential (GWP) and introducing the concept of quota, which refers to a reduction in the admissible production and import of HFCs in Europe over time. This has already led to an increase in prices and a decrease in the availability of high GWP refrigerants such as R-410A, driving the use of alternatives with a much lower GWP.

Lower GWP alternatives to R-410A for heat pumps include R-290 (propane), a high efficiency natural refrigerant with very a low GWP and zero ODP. The only drawback is its flammability, being in group A3 in accordance with ASHRAE Standard 34 [3]. IEC 60335-2-40 [4] specifies particular requirements for electrical heat pumps when using flammable refrigerants, updated on April 2018, with different requirements for systems depending on the propane charge. For instance, additional mechanical ventilation is compulsory for systems with between 1 kg and 5 kg of propane.

Efficiency is currently another important subject in standards, which impact both the reduction of indirect CO_2 emissions and the electricity bill. Ecodesign and Energy Labelling Directives in Europe are very active in the definition of new regulations for energy-using and energy-related products. There are two Ecodesign regulations that include the requirements for different types of heat pumps: ENER Lot 1 [5] and ENER Lot 21[6]. Both of these, in line with regulations for other HVAC/R applications, establish seasonal energy

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efficiency limits, thus taking into account the variations in outside air temperature over the year. This brings more precision to the procedure and more advantages from the use of variable speed technology, which is able to adapt energy consumption to the needs of the application. The Energy Labelling regulation for heat pumps [7] includes space heaters, combination heaters, packages of space heater, temperature control and solar device, as well as packages of combination heater, temperature control and solar device. The second stage of this Energy Labelling regulation came into force on 26 September 2019, when new energy labels for classes A+++ to D were required.

In this context, accurate unit design and choice of components plays an essential role when developing a heat pump, in order to optimise energy consumption and reduce total CO_2 emissions, while ensuring safety. The aim of this project was to develop an R-290 air-to-water residential heat pump with high performance, meeting all the required safety and usability goals for the use of flammable refrigerants on the European residential heating/cooling market.

2. Description of the project

This project was completed by our company in collaboration with a European customer, and lasted almost three years, including component selection, unit design, performance testing, certification, field testing and start of production. The field tests and most of the data taken outside of the laboratory referred to an area in central Germany area, with an annual average temperature of 9°C.

The unit described is an air-to-water heat pump, comprising a packaged outdoor unit, connected via fluid piping to an indoor unit equipped with a distribution system for space heating and cooling, and a water tank for domestic hot water storage.

The outdoor unit includes a refrigerant circuit equipped with variable-speed DC scroll compressor and electronic expansion valve.

Table 1 shows the other main characteristics of the unit:

Table 1. Summary of heat pump characteristics

Heat pump characteristic	Value
Refrigerant	R-290
Power supply	400V 3-phase
Heating capacity (A2/W35)	1.9 - 7 kW
Cooling capacity (A35/W18)	2.3 - 7 kW

The unit is also equipped with an electric heater for auxiliary use, for example to reach a water temperature of 70°C in the event of system request, or for use as backup, to guarantee continuous heating service for the end user even in the event of a unit fault. This heater was not activated during the comparison tests.

3. Test results

3.1. Comparison with R-410A unit

To perform this comparison test, an existing unit equipped with R-410A refrigerant and with the same nominal heating capacity as the heat pump studied (7 kW) was used as reference. The sample is a standard unit already available on the market, coupled with an indoor unit for fluid management and distribution. The scheme can be seen in Fig.1. In this section, for brevity, the R-290 unit is called “Unit A” and the one with R-410A “Unit B”. To perform the tests, we used the same indoor unit for both Unit A and Unit B. The data used for this comparison between the two units was acquired by certification testing laboratories. The characteristics are summarised in Table 2.

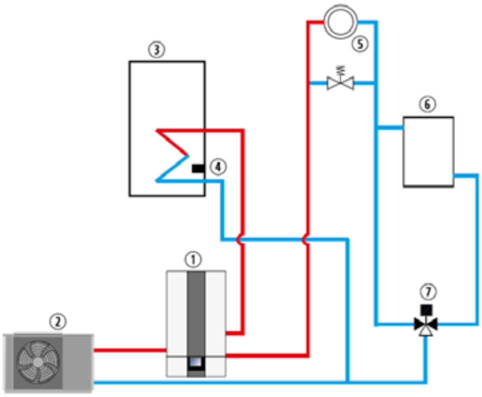

Fig. 1. Diagram of the fluid and distribution system used for the comparison test
1.Indoor unit | 2.Outdoor unit | 3.Hot water tank | 4.Storage tank sensor | 5.Heating circuit |
6.Intermediate water tank | 7.Three-way heating / cooling switching valve

Table 2. Summary of heat pump Unit A and Unit B characteristics

Heat pump characteristic	Unit A	Unit B
Refrigerant type / GWP	R-290 / 3	R-410A / 2088
Refrigerant charge	3.1 kg	2.15 kg
CO_2 equivalent	0.009 t	4.49 t
Heating operating limits (water)	+20°C to +70°C	+20°C to +55°C
Heating operating limits (air)	-22°C to +40°C	-20°C to +35°C
Cooling operating limits (water)	+7°C to +30°C	+7°C to +20°C
Cooling operating limits (air)	+10°C to +45°C	+10°C to +45°C

The most striking difference is the GWP value, i.e. the quantity of CO_2 that can be emitted into the environment. Considering that the two units have comparable power consumption (at -7°C air temperature, with a heating capacity of 6 kW, consumption of Unit A is 2.15 kW, and consumption of Unit B is 2.28 kW), the much lower GWP value makes Unit A the best solution to meet the emissions reduction requirements of the international agreements and regulations mentioned above.

Fig.2, Fig.3 and Fig. 4 show a comparison between the different efficiency levels in different test conditions.

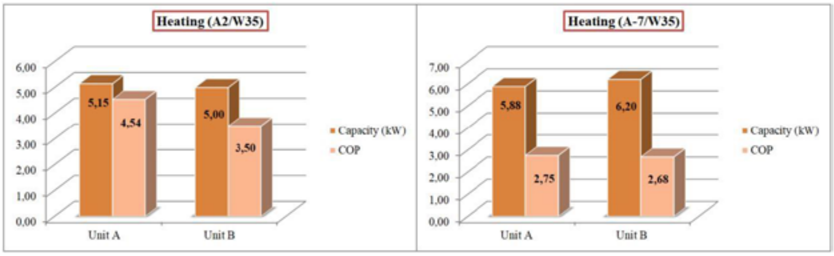

Fig. 2. Comparison test in heating mode. Nominal performance according to EN14511.

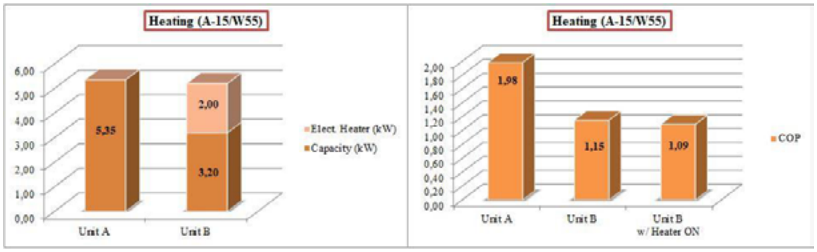

Fig. 3. Comparison test in heating mode with low air temperature.

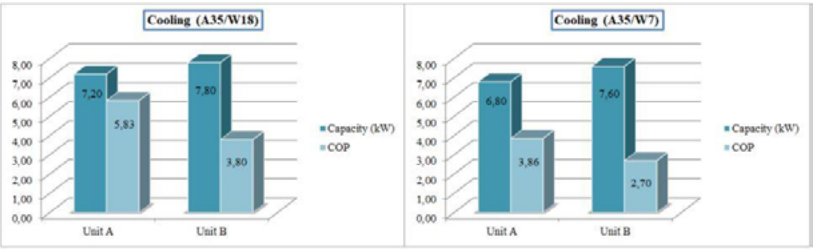

Fig. 4. Comparison test in cooling mode. Nominal performance according to EN14511.

The results shown in Fig. 2 indicate that, in both test conditions, the two units have a virtually identical heating capacity. The efficiency value is higher in Unit A, both with air at -7°C (+ 3%) and above all at + 2°C (+ 30%).

A significant difference is seen in working conditions with a low outside temperature, specifically -15°C: the characteristics of the refrigerant and compressor on Unit A allow a higher heating capacity and better efficiency than Unit B, as shown in Fig.3.

The results shown in Fig. 2 indicate that in both test conditions the two units have a comparable heating capacity: a difference of 1.5% with A2/W35, and 2.5% with A-7/W35. The COP value is higher for Unit A in both cases: +3% with A-7, +30% with A2.

An additional test was performed with lower outside temperature conditions, in order to highlight how the use of R-290, compared with R-410A, can avoid an excessive reduction in unit heating capacity.

The results are shown in Fig. 3. In test conditions A-15/W55 (high supply water temperature in cold climate conditions), Unit A has a capacity of 5.35 kW, with a COP value of 1.98, while Unit B has a capacity of 3.2 kW (40% lower than Unit A) with a COP value of 1.15. The electric heater on Unit B needs to be switched on (2 kW) in order to reach a comparable heating capacity between the two units, reducing the difference in capacity to 3%. However, this leads to a further reduction in the COP of unit B, which drops from 1.15 to 1.09.

The results shown in Fig.4 are related to cooling mode.

The comparison tests show that cooling capacity is a little bit higher in Unit B, +3.8% with W18 and +5.2% with W7. On the other hand, the COP coefficient measured is significantly higher in Unit A, +35% with W18 and +29% with W7 There are two important factors to consider when evaluating the results:

- The air heat exchangers on Unit A and Unit B are different in terms of size, design and plastic or polypropylene components used to guide the air flow inside the unit. We can assume by looking at the nominal performance data for the two heat exchangers that the one used on Unit A is +14% more efficient than the one used on Unit B;
- Unit B is equipped with a single EEV, used in two-way flow configuration so as to support both heating and cooling mode. In fact, the EEV is sized to assist operation in heating mode, in order to have the necessary flow control precision in the most extreme environmental conditions, such as high water temperature production with a low outside air temperature.
  Unit A is equipped with 2 EEVs: one is used in heating mode, the other in cooling mode. The EEV

for cooling mode can ensure an increase of 30% in the maximum allowable refrigerant flow rate, but at the same time a loss in control precision at low opening: each step of movement can increasingly affect the amount of refrigerant in the evaporator.
In this way, the modulation range for each EEV can be sized for the specific operating mode: this is especially useful in cooling mode, when performance is often not fully optimised in order to favour heating mode, considered the main operating mode.

3.2. Considerations about the use of R-290

Thanks to the operating envelope of the R-290 compressor, the two most significant values of extended operating range concern heating mode. A higher outside air temperature limit allows the production of domestic hot water even in the most severe summer conditions.

The most significant value concerns the higher hot water supply temperature, which has three main benefits:

- Production of hot water can also be used for systems with high temperature distribution systems, such as radiators. This allows the use of the unit in installations where the use of R-410A is difficult due to problems with high condensing pressure.

- It is possible to produce hot water with a temperature higher than 50°C even with an outside temperature below -15°C, with better efficiency than with the currently used refrigerants.

- The possibility to reach an outlet water temperature of 65-70°C, when conditions are favourable, to perform anti-legionella treatment on the domestic hot water without activating the electric heater: this means high energy savings for the system and therefore a considerable increase in COP.

4. Safety measures

One of most challenging issues of this project was the safe use of the electronic controls, devices and components normally used in HVAC applications, but not certified for compliance with EN 60079:15 [8] and EN 60335-2:40.

Appliances shall be constructed so that any leaked refrigerant will not flow or stagnate so as cause a fire or explosion hazard in areas within the appliance and connected ducts where electrical components, which could be a source of ignition and which could function normal conditions or in the event of a leak, are fitted.

These components shall comply with one of the following conditions:

- Components should be placed inside an enclosure which complies with Clause 20 of IEC 60079:15-2010;
- A test of Annex FF of EN 60335-2:40 must be performed with a leak simulation test: with this method must be demonstrated that a potentially flammable gas mixture will not accumulate;
- Components are compliant with Clause 16 to 22 of IEC 60079-15:2010.

The most critical components were the electronic control board and the compressor speed drive: both components are certified and fully eligible to be used for general HVAC residential applications. However, the presence of components that could be identified as possible spark sources, for example the relay, does not permit the use of these devices in the open air in this kind of application.

The solution selected follows the first of the conditions listed above: create a dedicated metal enclosure of dimensions and features compatible with its positioning within the outdoor unit. The most critical points of the panel design, construction and component selection are described as follows.

4.1. Panel tightness

First, it was necessary to guarantee tight closing of the panel, in order to avoid hazardous amounts of gas accumulated in critical concentrations inside. This is an issue that may occur in the event of malfunctions and leakages.

Fig. 5. Details of fixing system for the panel enclosure.

Fig.5 shows the details of the panel enclosure. The cover is equipped with an inner gasket, positioned around the entire inside perimeter. When the cover is positioned, the inner gasket is aligned exactly with the edge of the panel (see image on the left in Fig. 5), and after placement and fixing by the screws inserted in the side brackets (image on the right in Fig. 5), the gasket is pressed down by 3 mm, around 50% of its thickness. The position of soldered bracket guarantees the correct pressure of the bottom part of the enclosure against the cover gasket without any specific screw torque value: this makes it possible to guarantee panel tightness with a faster industrialised process, and only a visual check is performed on the presence of all 8 screws.

Furthermore, the size of the different cables needed for control of the unit may be the source of holes or openings that compromise insulation of the enclosure, creating a possible pathway that flammable gas can pass through and accumulate inside the enclosure: communication cables, sensors, driver cooling fan, compressor connection and panel power supply in general.

Fig. 6. Details of the connection kits for cable glands.

All cables connecting components inside the panel with the outside devices pass through specific cable glands, as shown in Fig. 6. The image on the left shows the outer part of the kit, while on the right is the inside view. The large rectangular gland with 8 subsections is a specific custom part, created to satisfy the specific combination of cables needed for these units. However, the gland comprises a main black part and inner grey parts: these are all standard components. This solution guarantees compliance of the enclosure with Clause 20 of IEC 60079:15-2010: the required degree of insulation is a subset of requirements for IP54 protection.

Except for the screw holes used for this gland and other holes made for compressor drive pass-through mounting or another specific cable glands, no other drilling operations are performed when manufacturing the enclosure: all of the screws present are welded directly onto the inside surface of the enclosure, in order to avoid further possible causes of loss of tightness.

At the end of enclosure manufacturing process, a negative pressure test is performed. During this test, automatic equipment is connected via a silicone pipe to the inside of the enclosure: the enclosure is de-pressurised until reaching a “pressure test setting”. The equipment then stops taking in air and starts checking the inside pressure value, so as to measure the volume of air that flows into the enclosure to rebalance the pressure. To guarantee compliance, the volume should be lower than 1.8 l/min, a value defined in relation to the size of the enclosure.

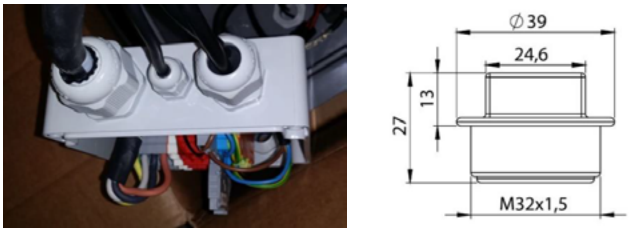

Fig. 7. Example of cable gland usage and selected model to satisfy requirements for correct enclosure usage in a residential heat pump.

Fig. 7 shows the junction box for power supply and serial communication connections. This box has been made separately from the main electrical panel as it must be guaranteed that installers or untrained personnel cannot open the enclosure in the field, especially during installation. This junction box is the connection point when placing the unit, in order to allow power connection to the supply line and serial connection for communication between the outdoor unit, where the enclosure is placed, and the indoor unit for fluid management, equipped with the control display.

For the junction box, the designers also selected a specific electrical box and cable glands compatible with this application, but at the same time easily purchasable on the market.

Table 3 shows some details of the connectors.

Table 3. Connector specifications.

Material	Polycarbonate (PC)
Flame class	UL94-V0, self-extinguishing
IP rating	IP54, with gasket and correct selection of the cable grommets
Temperature range	-30°C to +100°C
Properties	Halogen-free, silicone-free

4.2. Panel cooling

As the panel is sealed, it is necessary to guarantee correct heat dissipation from the panel in order to keep the contained devices in safe conditions. The compressor driver, due to its power consumption when operating, is the “hottest” critical point. The solution adopted was to use a driver equipped with pass-through ventilated heat sink system. In order to guarantee the air flow across the finned heat sink, two small fans are mounted on the front. The fan motors are insulated and compliant with the required clauses of the standards, so as to be used outside of the panel.

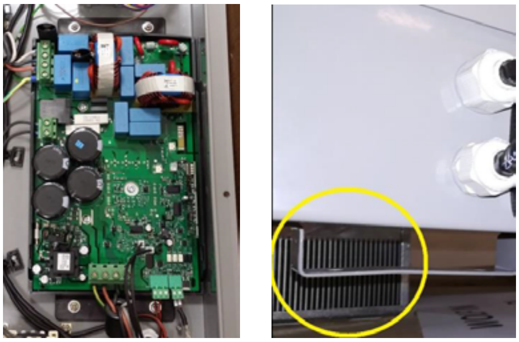

Fig. 8. Inverter drive placement in the panel and detail of pass-through heat sink.

To obtain this configuration, we used a standard device already equipped with a gasket underneath the moulded plastic base, which ensures tightness after fixing the drive to the panel using the special brackets. The only significant change was to use a plastic moulding for the base without holes for the cooling fan cables: the cables were passed through dedicated cable glands, of the type described above.

Using this specific base without holes and mounting the driver with correct positioning of the gasket around the hole, the tightness of the enclosure and IP54 protection were guaranteed when testing the complete panel solution.

With this equipment, the unit was tested up to the maximum outside air temperature allowed for operation (cooling mode): at 40°C the air surrounding electronic components does not exceed the limit threshold of 65°C. These values are compatible with the temperature operating range of the electronic components placed inside the enclosure.

5. Conclusions

The results of these tests, carried out in the field and in the laboratory, have shown how the use of R-290 refrigerant in heat pumps with packaged outdoor units is a fully usable, industrialised, efficient and safe solution. The high efficiency, low GWP and high energy yield values compared to traditional refrigerants, make these units optimal devices to reduce power consumption, increase system efficiency and contribute to a reduction in CO_2 emissions.

The goal for the near future is to expand the range of units in order to cover a greater variety of needs, maintaining the same structure presented above. At the same time, we are working, by mutual agreement with our customers and certification bodies, on further certification of standard components that can be used in specific HVAC applications in the presence of flammable refrigerants.

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Nomenclature

COP:	Coefficient Of Performance
EEV:	Electronic Expansion Valve
GWP:	Global Warming Potential
HFC:	HydroFluoroCarbon
HVAC:	Heating Ventilation Air Conditioning
IEC:	International Electrotechnical Commission
IP:	International Protection
ODP:	Ozone Depletion Potential

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