Technical Assistance to Plotter-Racks to Develop a Modular Chiller using the R-290

Final Deliverable: R-290 Chiller Final Design, Bill of Quantities and Estimated Cost

Task 3: Identification of components suppliers and their cost; estimate cost of modular chiller with R-290.

By

Omar Abdelaziz, Ph.D.

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Report Submitted to

Alessandro Amadio, UNIDO Representative for Brazil and Venezuela

Sérgia de Oliveira, Project Manager

Edgard Soares, National Expert in Refrigeration

In partial fulfilment of the duties for the TOR “Expert on modular chiller, based on R-290, for commercial refrigeration equipment”

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1 Introduction

A detailed engineering analysis for the development of a propane (R-290) modular air-cooled chiller showed that the R-290 chiller has the potential to provide superior performance over the baseline R-410A chiller. The detailed study considered 2 potential R-290 compressors and the impact of evaporator superheat on the system performance. The baseline R-410A system operating with the variable speed Danfoss VZH44CG compressor has a weather average COP of 2.92, at 4800 RPM and 8°C superheat, whereas the proposed R-290 system operating with the Emerson ZPB49KCU compressor has a weather average COP of 3.36, a 15% improvement in COP. The R-290 system runs at 3000 RPM with 6°C superheat. Furthermore, the R-290 system results in a weather- average cooling capacity of 14.5 kW whereas the baseline provides only 13.5 kW of weather-average cooling capacity. Finally, the R-290 chiller is expected to have an R-290 refrigerant charge of roughly 1 kg.

This report will summarize the assembly of the R-290 modular chiller, analyse product safety, identify components' suppliers and their estimated cost, estimate total cost of modular chiller with R-290, and discuss safe installation practices.

2 R-290 Modular Chiller Assembly

An isometric view of the R-290 modular chiller assembly is shown in Figure 1. The system comprises a compressor, shown in purple, a brazed plate heat exchanger (BPHX), shown in grey, a microchannel heat exchanger (MCHX), shown in green, an electronic expansion valve, shown in red, an isolating solenoid valve, shown in red, and a condenser fan shown in black.

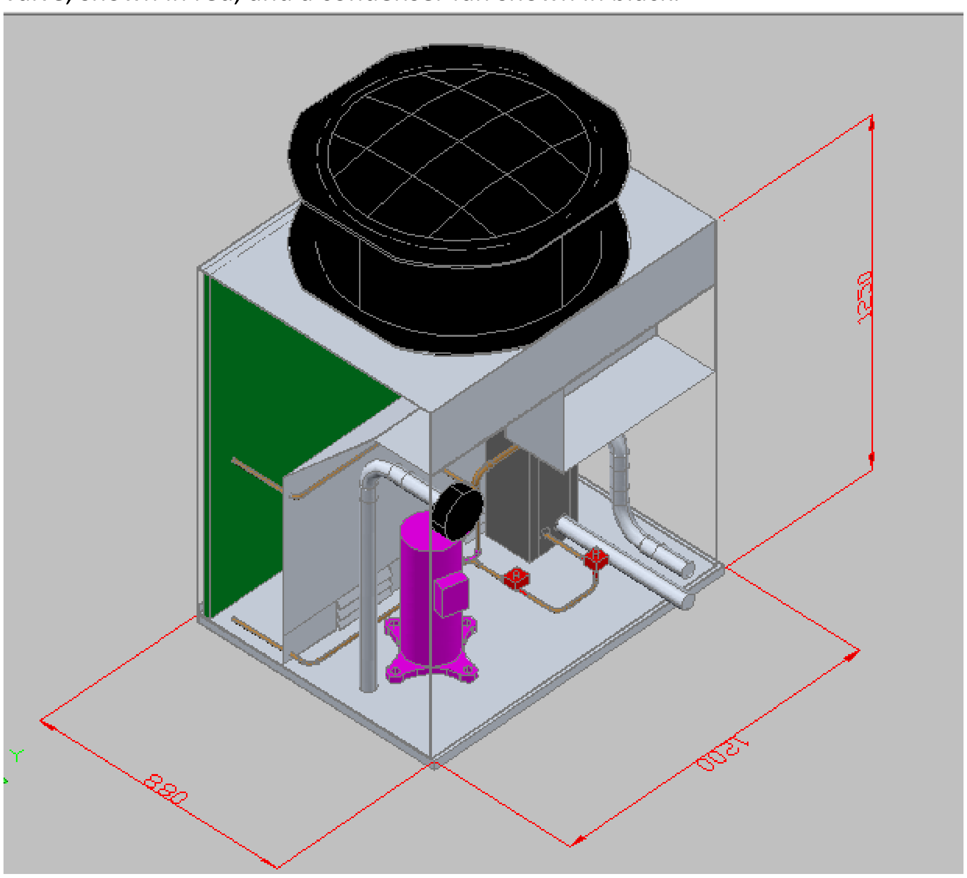

Figure 1: Isomeric view for the R-290 chiller assembly with external dimensions

The side view of the R-290 chiller is shown in Figure 2. It shows the propylene glycol chiller inlet and outlet pipes, as well as the additional safety components such as the air vents between the condenser chamber and the compressor and BPHX chamber and the emergency exhaust duct and ATEX blower. The front view of the R-290 chiller is shown in Figure 3; it further indicates the location of the propane leak sensor and the electrical box.

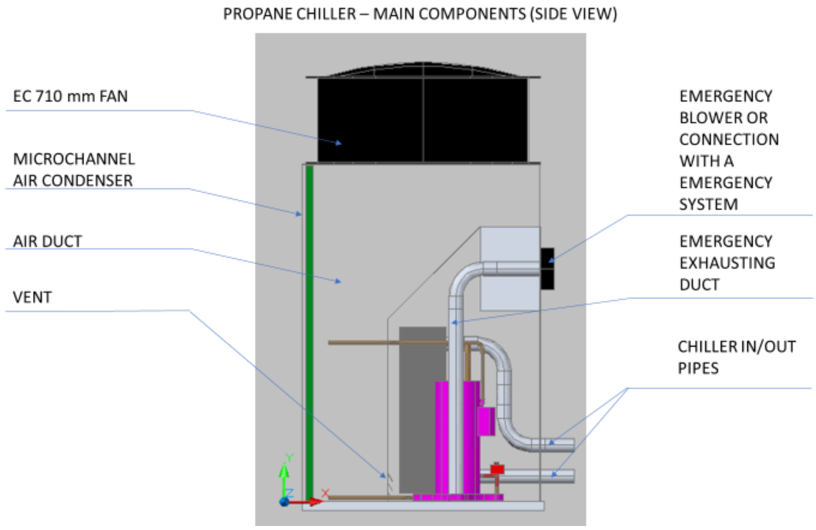

Figure 2: Side view of the R-290 chiller showing main vapor compression system components.

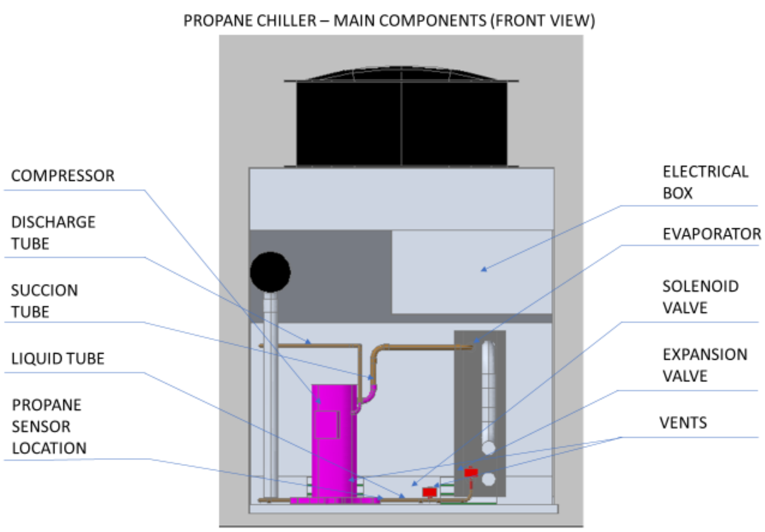

Figure 3: Front view of the R-290 chiller with the main components

3 R-290 Modular Chiller Safety Analysis

3.1 Worst Case Scenario

The current estimated refrigerant charge based on the BPHX, MCHX, and the estimated liquid and discharge lines are roughly 1.0 kg. Assuming an extra refrigerant charge hold-up in the compressor of 150 g; the total charge would be 1.15 kg. Also, considering the low vapor density of propane; it is found that for ambient temperature varying between 5 and 37 °C and ambient pressures varying between 0.098 and 0.12 MPa the minimum vapor density is 1.7 m^3/kg. this represents the worst-case scenario and would be used for the analysis.

Furthermore, it is required to define the refrigerant release time for the refrigerant to the ambient. The current safety standards assume a refrigerant leak time of 4 minutes[1]. Finally, we can assume a constant refrigerant release rate of $1.15 \times 1.7 \div 4 = 0.48875$ m^3/min or 29.325 m^3/hr since this results in the worst refrigerant dispersion potential[2].

3.2 Refrigerant Release Location

There are four main refrigerant locations as shown in Figure 4:

- From the MCHX condenser towards the ambient (highlighted in yellow in Figure 4)
- From the BPHX evaporator towards the propylene glycol loop
- From the MCHX condenser or the high-side pressure pipe connections towards the sealed machine box (highlighted in green in Figure 4)
- From the within the remaining vapor compression components and pipes (highlighted in blue in Figure 4)

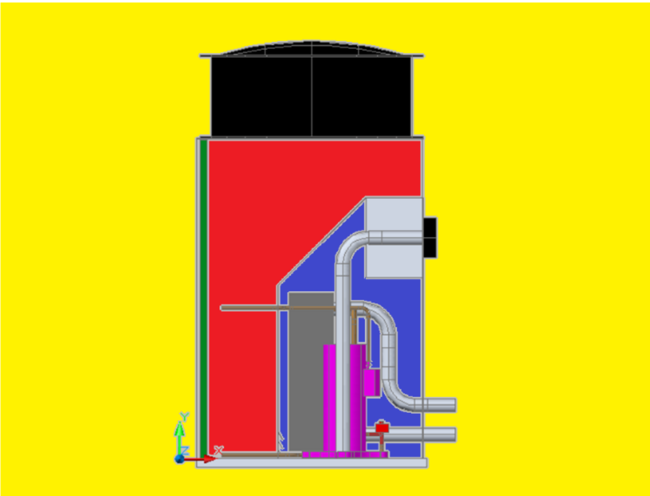

Figure 4: Refrigerant release zone; yellow: ambient, red: machine box volume A; blue: machine box volume B

[1] ISO 5149-2 and IEC-60335-2-40

[2] Elatar, A., Abu-Heiba, A., Patel, V., Dean, E., Baxter, V., Abdelaziz, O., Zhang, M., "Evaluation of flammable volume in the case of a catastrophic leak of R-32 from a rooftop unit", International Journal of Refrigeration, Volume 91, 2018, Pages 39-45, ISSN 0140-7007, https://doi.org/10.1016/j.ijrefrig.2018.04.024.

3.3 Refrigerant Charge Limit

The R-290 modular chiller design's refrigerant charge limit is primarily controlled by the ISO 5149 international safety standard. The allowable refrigerant charge depends on the maximum (M_{max}) and allowable (M_{al}) charge prescribed in the corresponding standards. The M_{max} is a function of the equipment, location, and occupancy, the M_{al} is a function of room size and refrigerant release location. Furthermore, M_{max} and M_{al} depends on the LFL, summarized in Table 1 below for relevant R-290.

Table 1: Flammable and practical limits of relevant HC refrigerants

Value	R-290
LFL, kg/m^3	0.038
LFL, %	2.1[3]
UEL, %	9.5[3]
Autoignition temperature	450°C[3]
Minimum ignition energy (MIE)	0.25[4]
PL/RCL, kg/m^3	0.0095
Density of vapour at standard pressure, kg/m^3	1.86
Worst case density of vapour, kg/m^3	1.7

The installation of the R-290 modular chiller has to be under category C of Standard 5149: occupancy with authorised access only. Table 2 provides a summary of the allowable and maximum refrigerant charge for this different configuration of non-comfort equipment based on ISO 5149 for installations above ground. Below ground installation have M_{max} of 1 kg and M_{al} of PL x V_{Rm} for direct systems and 1 kg for indirect systems. As seen from Table 2, there is no limit for refrigerant charge for the modular chiller design since it follows the indirect system of Category C.

Table 2: Summary of M_{max} and M_{al} according to ISO 5149 for non-comfort equipment

Occupancy type	System type	M_{al}, kg	M_{max}, kg
Category A	Direct	PL × VRm	1.5
Category A	Indirect	5	5
Category B	Direct	PL × VRm	2.5
Category B	Indirect	10	10
Category c	Direct	PL × VRm	10 or 25*
Category c	Indirect	No limit	No limit

V_{Rm} is the room volume

* 25 kg if compressor and liquid receiver are in an unoccupied machinery room or in the open air

[3] http://www.refrigerants.com/pdf/SDS%20R290%20Propane.pdf
[4] https://www.jraia.or.jp/english/side/presentation3.pdf

Furthermore, to ensure adequate ventilation and minimise the risk of developing a flammable atmosphere, the following air flow is required especially in tight and enclosed areas.

$V_{min} = 0.004 \times M \div LFL = 0.004 \times 1.15 \div 0.038 = 0.1211 m^3/s = 436\ m^3/hr$

Where V_{min} is the minimum required air flow in m^3/s, M is the refrigerant charge in kg, and LFL is the lower flammability limit in kg/m^3 as defined in Table 1.

The design flow rate for the condenser fan of the R-290 modular chiller is 9700 m^3/hr, hence under the worst-case scenario of refrigerant release rate of 29.325 m^3/hr, the flammable refrigerant to air ratio is 29.325/9700 = 0.003. This is well below 25% of the LFL and as such it can be safely dispersed through the condenser fan. **It is important that the condenser fan control be interlocked with the R-290 refrigerant leak detector, such that in cases of reduced condenser fan speed or during system off-time the condenser fan is activated at full speed (9700 m^3/hr) when the refrigerant leak detects 10% of the LFL in the volume B of the machine box.**

Furthermore, an emergency ATEX ventilation fan should be installed with a minimum volumetric air flow of 436 m^3/hr. This fan should draw the air/refrigerant mixture from the bottom of volume B of the machine box (5 – 10 cm clearance from the bottom) towards the ambient at a point higher than the equipment. Note that the louvered vents between the volumes A and B of the machine box play 3 important roles. First it allows for using just one refrigerant leak sensor in volume B. during off-periods, the air is still in volume A, and when refrigerant leaks – it is expected to flow towards the bottom of the cavity since R-290 is heavier than air. As such, it will disperse through these louvered vents and dissipate towards the refrigerant leak sensor which would indicate an alarm accordingly. Second, it allows the emergency ventilation fan to maintain safe environment within the machine box by allowing ambient air to flow through the MCHX then through those louvered vents before mixing with the leaked refrigerant in volume B. Third, the louver vents would allow the emergency fan to maintain safe environment within volume A if the condenser fan could not be operated during the off period.

3.4 System Installation Best Practices

This section presents some guidance based on ISO 5149 and IEC 60335-2-89 including:

- Outdoor installations
- Machinery rooms

3.4.1 Outdoor installations

Outdoor installation should be protected against potential mechanical damage and provide adequate means for risk management in the event of refrigerant leakage.

- Refrigerant-containing and critical parts of the equipment must be protected from mechanical damage
- Equipment housing should be robust and resistant to weather and other forms of damage
- Equipment should be positioned at a safe distance from items that may be negatively affected by a release of refrigerant
- Ensure free ventilation all around the equipment, and avoid permanent or temporary blockages
- The area should be free of combustible materials

- Due consideration should be given to drains and lower terrains, in case escaped refrigerants could pass through them and accumulate
- Careful consideration should be given to the positioning of the equipment with regards to opening to other buildings, duct inlets, vents, etc

When accessible by members of the public additional criteria should be considered:

- The charge of individual refrigerant circuits should not exceed the values specified Table 2
- The equipment housing should prevent or inhibit interference from others
- Avoid proximity to areas where people may congregate

For equipment located in an area accessible by authorised personnel only, the following criteria should be considered:

- Access to the area should be controlled
- The controlled area should have a radius of between 2 m to 5 m away from the equipment, depending upon the charge size and the design of the equipment

The minimum "safe" distance, d (m) may be approximated as

$$d = C_w \times \sqrt{\frac{M_c}{\pi \times h_{enc} \times LFL}}$$

where M_c is the refrigerant charge per individual circuit (kg) and h_{enc} is the height (m) of the enclosure or fence surrounding the system. Note that fence should be located within the "safe" distance. When no fencing is present, the height of the unit housing may be used for the calculation. The constant C_w depends on the local airflow conditions:

- Sheltered location, such as besides or between buildings, $C_w \approx 0.5$,
- Exposed location, such as on a roof, $C_w \approx 0.25$.

For the R-290 modular chiller, the $M_c = 1.15$ kg, $h_{enc} = 1.25$ m (assuming no fence surrounding the system) hence the safe distance is equal

- $d = 0.5 \times \sqrt{\frac{1.15}{\pi \times 1.25 \times 0.038}} = 1.39$ m for sheltered locations, or
- $d = 0.25 \times \sqrt{\frac{1.15}{\pi \times 1.25 \times 0.038}} = 0.7$ m for exposed locations.

3.4.2 Machinery rooms

Machine room installations usually require adherence with local and national regulations. When HC equipment are located within machinery room, additional requirements are imposed. These are largely related to the potential flammable mixture and the required measures to avoid potential ignition. In general:

- In the case of potentially reaching the LFL, the installation should comply with the requirements for hazardous areas
- Avoid sources of ignition inside the machinery rooms

- Combustion equipment such as boilers are considered SOIs; as such they can't be co-located within the same machinery room as an HC refrigerating system
- Piping and ducting passing through walls, ceilings and floors must be tightly sealed to avoid refrigerant leakage spill over to other enclosed or occupied areas
- Eliminate air intakes for any equipment from within the machinery room
- Precautions must be taken to prevent leaked refrigerant that is denser than air entering into drainage systems
- Voids in the machinery room floor should be avoided, or designed so that heavier than air refrigerant could not accumulate in these spaces in the event of a leak

Employ proper safety control measures in the machinery room to enable proper risk management during flammable refrigerant release. This includes: flammable refrigerant detection, alarms, electrical interlock, and ventilation fan.

Additional features for the machinery room considering HC refrigerants include:

- Direct access to outdoors when the refrigerant concentration higher than 20% of the LFL is detected
    - If not possible, then it should be through a dedicated vestibule equipped with self-closing, tight-fitting doors
- To improve dispersion and minimise the severity of the ignition event, ensure that a large open wall area is available; ideally at least 50% of the area of one of the walls should be open, and preferably close to 100%
    - Open area may be fencing, grilles, etc, but should not pose any resistance to the free-flow of air
- If there is any less than 25% of the total (four walls plus ceiling) area that is not open, then some explosion relief must be provided if the refrigerant charge would result in flammable concentration reaching the LFL. This would ensure that in case of deflagration or explosion, a controlled failure will occur preventing severe damage to the building
    - This explosion relief may be in the form of a frangible wall or roof, which should have very low mass and weak fixings, and should require a force of less than around 20 kPa to open
- The access to the machinery room should be permitted for suitably trained, authorised persons only

4 R-290 Modular Chiller Components List and Cost Estimate

The R-290 modular chiller is similar to the existing R-410A Chillpack design in many aspects except for the added safety features and specialized components such as the compressor and the emergency ATEX ventilation fan. Below is a table that summarizes the main components of the R-290 modular chillers with the potential supplier name and cost.

Table 3: Bill of quantity for the modular R-290 chiller

	Component	Supplier	Cost (USD)
Vapor Compression System	Compressor	Emerson (ZB49KCU) Or Mitsubishi-Carel (APB52FA1MT)	880†
	electronic expansion valve	Danfoss ETS 6-18	22
	MCHX Condenser	Sanhua	547
	BPHX evaporator	SWEP	260
	Refrigerant cost		17
	condenser fan	ZIEHL-ABEGG (ZN071ZIL.GG.V7P4)	607
	glycol pump		302
Electric and electronic components	Control system cost		350‡
	contactors, relays, sensors, wires etc.		495‡
	Inverter		470‡
Balance of system cost	piping and tubes		77‡
	frame and balance of system cost, electric panel cost		1070‡
Additional safety features	Emergency Extraction fan	Shenli Electrical Technology Co., LTD[5] (ATEX-PROOF EXTRACTION FAN SLJF CTF-20)	40*
	Cost premium for high protection grade electrical box		50
	Cost premium for spark free contactors, relays, and pressure switches		100
	Cost premium for machine box sealing		50
	Refrigerant leak detector	TZT, MQ-6 solid state sensor	1.09††
	Ultrasonic refrigerant leak detector		50**

†Estimated based on previous discussion with supplier

‡Estimated based on previous experience with the Chillpack.

* https://www.alibaba.com/product-detail/industrial-air-ventilation-fan_60445886918.html

†† https://www.aliexpress.com/item/1pcs-MQ-6-LPG-Gas-Sensor-Module-Liquefied-Propane-Iso-butane-Butane-Combustible-Gas-Detection-Sensor/32776943025.html?ws_ab_test=searchweb0_0,searchweb201602_5_10152_10065_10151_10344_10068_10342_10343_10546_10340_10059_10341_10548_10696_100031_10084_10083_10103_10618_10307_10624_10623_10622_10621_10620,searchweb201603_1,ppcSwitch_5&algo_expid=2508b014-d85a-44f2-bddb-fc304eb67395-0&algo_pvid=2508b014-d85a-44f2-bddb-fc304eb67395&transAbTest=ae803_2&priceBeautifyAB=0

** Estimates based on available handheld ultrasonic equipment e.g. (https://www.aliexpress.com/item/all-sun-EM282-Ultrasonic-leak-detector-40KHz-ultrasonic-transmitter-relative-humidity-80-reliable-detection-gas-leak/32299193639.html?ws_ab_test=searchweb0_0,searchweb201602_5_10152_10151_10065_10344_10068_10342_10343_10546_10340_10548_10341_10696_10084_10083_10618_5725020_10307_5724920_5724120_5724020_10059_5724720_100031_5724320_10103_10624_10623_10622_10621_10620_5724220,searchweb201603_1,ppcSwitch_5&algo_expid=0b55376f

[5] http://www.chinashenli-ex.com/

-2dec-495c-b37d-993b77f57aa0-1&algo_pvid=0b55376f-2dec-495c-b37d-993b77f57aa0&transAbTest=ae803_2&priceBeautifyAB=0)

As such, the total cost of the components for the modular chiller is estimated at $5388.09.

5 Conclusions

A modular R-290 chiller design is envisioned to follow the same design for the current Plotter-Racks Chillpack R-410A product line. The R-290 chiller components are expected to cost roughly $5400. The system design incorporates an additional emergency exhaust fan, a refrigerant leak detector, and an ultrasonic leak detector. Furthermore, the machine box where the vapor compression system components are located is well-sealed. Furthermore, louvered vents are added between the condenser box and the remaining vapor compression system box.

With respect to the installation safety, the safe distance is calculated as 1.4 m in cased of sheltered locations (e.g. installations between buildings) and 0.7 m for exposed surfaces (e.g. installations on rooftops)

6 Additional Resources:

Abu-Heiba, A., Patel, V., Baxter, V., Abdelaziz, O., Elatar, A., “Setting Charge Limits for Flammable Refrigerants”, ASHRAE Journal, Volume 60, Issue 7