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(54) A COMPUTER IMPLEMENTED METHOD, A COMPUTER PROGRAM, AND A SYSTEM FOR MONITORING REFRIGERANT GAS LEAKS IN A REFRIGERATION SYSTEM

(57) The present invention relates to a computer implemented method for monitoring refrigerant gas leaks in a refrigeration system, comprising:
- detecting a refrigerant gas leak within a predetermined volume and measuring, along time, a concentration of said detected refrigerant gas leak within said predetermined volume; and
- estimating the severity of said detected refrigerant gas leak by computing a leak severity indicator that relates said concentration measurements to refrigerant gas leak intensity represented by estimations of mass leaked over time within said predetermined volume.

The present invention also relates to a computer program and a system for monitoring refrigerant gas leaks in a refrigeration system which implement the method of the invention.

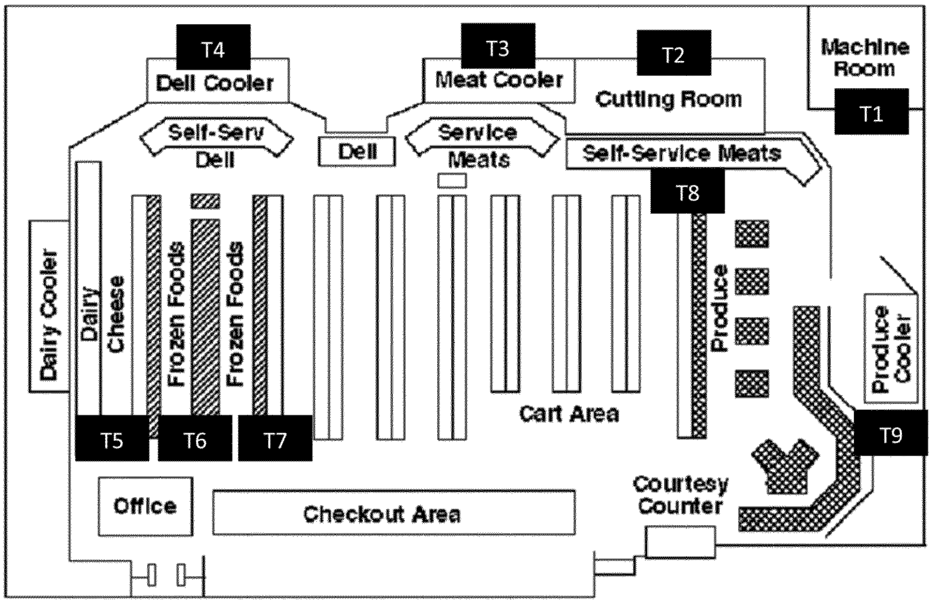

Figure 3

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Description

FIELD OF THE INVENTION

[0001] The present invention generally relates, in a first aspect, to a computer implemented method for monitoring refrigerant gas leaks in a refrigeration system, and more particularly to a method which provides an estimation of the severity of the leak.

[0002] A second and a third aspect of the invention respectively relate to a computer program and a system for monitoring refrigerant gas leaks in a refrigeration system which implement the method of the first aspect of the invention.

BACKGROUND OF THE INVENTION

[0003] The European Union (EU), led by the F-Gas regulation, is nowadays under a strict HFC phase-down quota-production system which is inflicting a high inflation on HFC refrigerants (some of them becoming unavailable). Such scenario depicts how international refrigerant markets will evolve, since the Kigali amendment will impose a HFC phase-down worldwide. Indeed refrigeration stakeholders are now facing in Europe a HFC refrigerant market shrinkage without clear technological alternatives, becoming an unprecedented challenge for the sector, as the widely used HFC refrigerants are becoming extremely expensive or even unavailable. More concretely, refrigeration end-users, owners of several thousands of HFC-based commercial and industrial refrigeration installations with high or very high leak rates (between 15% and 35% of total charge per year) depend upon big amounts of fresh refrigerant to replace the leaked quantities, refrigerant that is needed in order to maintain both refrigeration systems and their business models operational. This is especially troubling for refrigeration installations that were designed and commissioned during the last 10 years (not fully amortized) that are fully operational and efficient, despite their leakages and their dependency upon big amounts of refrigerant. The sector is now timidly facing the problem in two different ways, a) retrofitting the refrigeration systems (usually without sufficient good practices) with lower-Global Warming Potential (GWP) HFC blends, despite decreasing the system efficiency and, sometimes, safety; and b) dismantling the HFC-based systems to shift towards new refrigeration system based on natural refrigerants (especially CO_2 and centralised transcritical CO_2) or mildly flammable HFO refrigerants. Unfortunately, both approaches are not either definite or, at the present moment, general. On the one hand, retrofits are still based on HFC-blends, which will keep becoming more expensive and hardly available as HFC Phase-down goes ahead in the next years. On the other hand, a complete conversion of all refrigeration installations towards natural/mildly flammable refrigerants might be possible although in a time lapse between 10-15 years, as per technical reasons (for instance, there is still a general current lack of know-how among small and medium- sized installers and contractors concerning new refrigerants) and - most importantly- due to financial aspects; remarkably for those refrigeration systems still not fully paid / amortized.

[0004] Refrigeration end-users are, therefore, facing a challenging scenario where decisions are difficult to make.

[0005] It is, therefore, necessary to provide an alternative to the state of the art which covers the gaps found therein, by providing a method and a system which goes beyond the simple detection and monitoring of refrigerant gas leaks, by providing an estimation of the severity of the leak, which makes easier those decisions for the refrigeration end-users.

SUMMARY OF THE INVENTION

[0006] To that end, the present invention relates, in a first aspect, to a computer implemented method for monitoring refrigerant gas leaks in a refrigeration system, comprising:

- detecting a refrigerant gas leak within a predetermined volume and measuring, along time, a concentration of said detected refrigerant gas leak within said predetermined volume; and
- estimating the severity of said detected refrigerant gas leak by computing a leak severity indicator that relates said concentration measurements to refrigerant gas leak intensity represented by estimations of mass leaked over time within said predetermined volume.

[0007] According to an embodiment, the method of the first aspect of the invention comprises computing the above mentioned leak severity indicator based on a mass conservation model that relates concentration values to refrigerant gas leak intensity, within a volume, density of the refrigerant gas, and modelled diffusion and convection terms, A and B, of the refrigerant gas which leaves said volume.

[0008] For an embodiment, the above mentioned computing of the leak severity indicator comprises extrapolating the same from a plurality of modelled values for the mean time integral of said diffusion and convection terms, *A* and *B*, for a corresponding plurality of values of reference concentrations c_{ref}, and reference volumes V_{ref}.

[0009] According to an implementation of said embodiment, said extrapolation is performed by computing the following equation:

$$\overline{L(T)} = \frac{c}{c_{ref}} \frac{V}{V_{ref}} \frac{1}{T} \int_0^T A(t, c_{ref}) + B(t, c_{ref}) dt$$

where c stands for the concentration measurements, *V* for the predetermined volume, *T* is a finite filtering/averaging period of time, $\overline{L(T)}$ is the refrigerant gas leak intensity averaged along *T*, and $A(t, C_{ref})$ and $B(t, c_{ref})$ are said diffusion and convection terms, *A* and *B*, for the reference concentration C_{ref} and reference volume V_{ref} to be integrated for a time *t* going from *0* to *T*.

[0010] For an embodiment, the leak severity indicator is $\overline{L(T)}$, expressed as the estimation of leaked refrigerant mass per hour, while for an alternative or complementary embodiment the leak severity indicator is a Leak Potential Index (LPI) computed from $\overline{L(T)}$ as the estimation of leaked refrigerant mass per year, or the estimation of equivalent tones of CO_2 per year (assuming the leak is constant and remains unattended throughout the following year).

[0011] According to an embodiment, the method of the first aspect of the present invention comprises computing a further leak severity indicator which is a Leak Charge Index (LCI) obtained by dividing the Leak Potential Index (LPI), when expressing the estimation of leaked refrigerant mass per year, by the total charge of refrigerant of the refrigeration system.

[0012] For an embodiment, the method of the first aspect of the present invention further comprises locating the refrigerant gas leak by performing the above mentioned detection and measuring step with several refrigerant gas detectors placed at different locations and forming at least one set of *n* refrigerant gas detectors configured and arranged for operating for the above mentioned predetermine volume, and triangulating the refrigerant gas leak spatial coordinates from the concentration measurements provided by the several refrigerant gas detectors and the spatial coordinates thereof.

[0013] For an implementation of said embodiment, the method comprises carrying out the above mentioned triangulation based on the different time-concentration behaviour of the refrigerant gas detectors.

[0014] According to a variant of said implementation, the method of the first aspect of the present invention comprises carrying out said triangulation by sequentially performing the following steps:

- detecting a refrigerant gas concentration change by means of any of said refrigerant gas detectors,
- assigning and starting a positive count-down decreasing time t_{leak} to at least all of the refrigerant gas detectors forming the at least one set;
- detecting, for each refrigerant gas detector *n*, that a concentration steady-state $\overline{c^n}$ has been reached for the refrigerant gas concentration measured thereby, and at that moment checking the value of the count-down decreasing time t_{leak}^n for the corresponding refrigerant gas detector *n*,
- obtaining the value of a time-stabilisation concentration variable TC^n for each refrigerant gas detector, by means of the following equation:

$$TC^n = (t_{leak} c)^n = t_{leak}^n \cdot \overline{c^n}$$

- correlating all the TC^n values obtained with the respective x, y and z refrigerant gas detectors spatial coordinates,
- applying a polynomial regression model to the obtained correlated points, to obtain at least three fitting polynomial $TC^{fit}(x)$, $TC^{fit}(y)$, $TC^{fit}(z)$, one per spatial coordinate, and
- performing a maximum analysis of each of the three fitting polynomial $TC^{fit}(x)$, $TC^{fit}(y)$, $TC^{fit}(z)$, and, from the results provided with said maximum analysis, determine that the refrigeration gas leak spatial coordinates are those which correspond to the ones for which said fitting polynomial $TC^{fit}(x)$, $TC^{fit}(y)$, $TC^{fit}(z)$ present a maximum, or, if no maximum is presented, the one for which a refrigerant gas leak preferred orientation is derived.

[0015] For an embodiment, the method further comprises computing a leak time indicator expressed by means of a Time-Gas Concentration Index (TGCI) by hourly averaging during several days the measured refrigerant gas leak concentration.

[0016] A second aspect of the present invention relates to a computer program, comprising program code instructions that when run in a computer or a processor implement the steps of the method of any of the previous claims.

[0017] In a third aspect, the present invention relates to a system for monitoring refrigerant gas leaks in a refrigeration system, comprising:

- at least one refrigerant gas detector configured and arranged for detecting a refrigerant gas leak within a predetermined volume, measuring, along time, a concentration of the detected refrigerant gas leak within said predetermined volume, and providing corresponding electrical signals representative of the concentration measurements; and
- at least one computing entity configured and arranged to receive said electrical signals, retrieve data representative of said concentration measurements therefrom, and for process said data according to the method of the first aspect of the present invention.

[0018] According to an embodiment, the at least one computing entity comprises storage means for storing data representative of said plurality of modelled values for the mean time integral of the diffusion and convection terms, A and B, and of the corresponding plurality of values of reference concentrations c_{ref}, and of the reference volumes V_{ref}, and wherein the at least one computing entity is adapted to process the stored data to extrapolate the leak severity indicator therefrom according to any of the above described embodiments of the method of the first aspect of the present invention.

[0019] For a further embodiment, the system of the third aspect of the present invention comprises a graphical user interface operatively connected to the computing entity to graphically display values obtained for any of the above mentioned leak severity indicator, further leak severity indicator, and/or leak time indicator.

[0020] By means of the present invention, an additional low-cost alternative to the prior art methods/systems is provided: a method/system to detect and localize refrigerant gas leaks at very early stages and, consequently, prevent refrigerant gas leakage in sensitive amounts without the need of constant, expensive and, sometimes, unfruitful maintenance leak inspections. Moreover, proper leak categorization through the computing power (for example, on an internet-server or cloud system) relating concentration readings (particles per million: ppm) with leak intensity (kg/year) is provided for some embodiments, which allows to optimally manage the leak information, prioritising inspection and repair resources based on the severity of the leak. A proper use of the method/system will help to maintain the refrigerants inside the cooling system with only few selective and precise interventions on the refrigeration facility.

[0021] It is important to mention that, as carried out according to the present invention, correlating the severity of the leak (L in g/h or kg/year) is meaningful because:

1. The environmental and economic impact of the refrigerant gas leak is only based on the mass of refrigerant (in kg) that is vented to the atmosphere and, therefore, related to green-house effects, on the one hand, and to refrigerant replacing, on the other, in order to avoid the refrigeration system to run inefficiently at under-nominal charge.
2. The concentration level is only relevant for safety reasons. For refrigeration applications, most of the costly and highly contaminant HFC & HCFC refrigerants may become mildly toxic beyond 10 000 ppm, i.e. among three and four orders of magnitude above the typical refrigeration gas leak concentrations, that may be under 10 ppm for important leaks (having important economic and environmental impacts for the owner of the system).

[0022] Hence, it is also important to note that the present invention is able to generate both types of information, concerning environmental/economical and safety points of view (as the concentration level is preferably also reported), being the latter the only approach nowadays in refrigeration applications.

[0023] For some embodiments, the system of the third aspect of the present invention prioritizes detected refrigerant gas leaks in a parametric manner (modifiable by the stakeholders of the refrigeration system, based in severity, time, location and safety aspects of the leak, among others) and consequently informs, warns and alerts a list of selected stakeholders using cellular telephony and/or internet technology (such as but not limited to 3G, 4G, 5G, Narrow Band based, SMS, e-mail, telegram app, etc.).

[0024] The system of the third aspect of the present invention is also able, for some embodiments, to trace the refrigerant gas leak as explained above, i.e. by convoluting/triangulating surrounding networked sensors/transmitters which might help to indicate the most probable leak position (for example in supermarket ceilings, leak information of three or more sensors/transmitters in a common confined ceiling area will be used to triangulate the potential leak spot) thus exponentially minimizing repair time to locate the leak, therefore minimizing refrigerant vented to the atmosphere.

[0025] The system of the third aspect of the present invention, for some embodiments, is also able to identify the most probable time of the day/week/month for the refrigerant gas leak to happen based on statistical analysis of concentration readings, therefore being able to indicate the most probable leak time (this is especially useful when leaks are related to specific refrigeration maneuvers that are not constant in time).

[0026] For some embodiments, the system of the third aspect of the present invention is also able, for example through internet technology, to summon leak information of different sensor/transmitter sets based on installation, location, company, contractor, etc. helping to analyze/compare leak-related failure rates and therefore maintenance or construction standards based on such criteria.

BRIEF DESCRIPTION OF THE FIGURES

[0027] In the following some preferred embodiments of the invention will be described with reference to the enclosed figures. They are provided only for illustration purposes without however limiting the scope of the invention.

Figure 1. (a): Visual display for the TGCI indicator, showing the most probable leak time at 13h; (b) Visual display for LPI and LCI indicators.
Figure 2. R448A concentration inside a supermarket cold-room between 9th and 14th May 2018.
Figure 3 describes the implantation of the gas sensors/transmitters in a typical commercial refrigeration system, where 9 different gas sensor/transmitters cover the compressor rack room and 9 different cooling services (evaporators) of the supermarket.
Figure 4 schematically illustrates an embodiment of the connected refrigerant leak early detection system of the third aspect of the present invention, using a wired bus (RS485 bus or similar using MODBUS communication protocols or similar).
Figure 5 schematically illustrates another embodiment of the connected refrigerant leak early detection system of the third aspect of the present invention, using a cellular telecommunication based network.
Figure 6 schematically illustrates the connected refrigerant leak early detection system of the third aspect of the present invention for a further embodiment, using a Wi-Fi based network.
Figure 7 schematically shows the location of four sensors/transmitters for an embodiment of the system of the third aspect of the present invention, used as an example for describing the leak location process of the present invention.
Figure 8 is a graph displaying the time evolution of the four sensors/transmitters of the neighbourhood set of Figure 7.
Figures 9, 10 and 11 are plots displaying the stabilized time-concentration values with respect to the three-coordinates for the example of Figure 7, in the form of x-dependence, y-dependence, and z-dependence curves, respectively
Figure 12 schematically displays the leak positioning by convolution/triangulation followed for the embodiment of Figures 7 to 11, the solid dot representing the determined refrigerant gas leak location.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0028] In the present section, some preferred embodiments of the present invention will be described, for specific implementations of the system of the third aspect of the invention, which is called below as "smart early detection system", and of the method of the first aspect, for which equational developments leading to the equations included in the claims and in a previous section are provided and explained in detail.
[0029] That specific implementation of the system of the third aspect of the invention, or "smart early detection system", is first described below.

Components of the smart early detection system:

[0030] The smart early detection system for gas leaks in refrigeration applications proposed by the third aspect of the present invention is composed, for the here described working embodiment, by three main components: *i*) on-site early detection by means of sensitive sensors/transmitters, *ii*) a connectivity method to communicate the on-site information to a third component: *iii*) a computing platform where the information is registered, analysed and leak indicators are computed. The three components are briefly described below for a specific implementation.

- *Refrigerant sensor* & *transmitter network:*

[0031] There are several technologies for detection of refrigerants in general and HFC in particular. The refrigeration sector has historically and widely used the semi-conductor or Metal Oxide Semiconductor (MOS) technology for refrigerant detection. This technology is limited by several drawbacks and it cannot be used by an early detection system, as namely selectivity, sensitivity, precision and accuracy are slightly poor and detection below 50 ppm is not possible and/or related to many false alarms due to the limited selectivity of the target gas by MOS technology. As further discussed, refrigerant early detection systems require sensitivity thresholds below sometimes even 20 ppm, therefore requiring technologies such as NDIR (Non Dispersive Infrared) or PIR (Photoacoustic Infra-Red), where sensitivity is below 10 ppm and both selectivity and accuracy are generally high or very high. For brevity, further discussions about the *pro* and *cons* related to gas detection technologies are here dismissed. The specific implementation of the system here presented makes use of a distributed network of NDIR sensors with accuracy/precision below 2% error, high selectivity and sensitivity below 5 ppm. The sensors are integrated into an on-site robust filtering device (transmitter) that reads the sensor information such that it can be communicated via different means, as discussed below.

- *Connectivity:*

[0032] The connectivity between the on-site sensing devices/transmitters and the computing platform (described further below) is very important in terms of system performance, and is also related to system robustness and, obviously, acquisition cost. The connectivity being a critical accessory of the smart early detection system, the system here in consideration is able to connect the network of on-site transmitters and the computing platform in different ways, wired or wirelessly (such as by means of Wi-Fi or mobile telecommunication networks), although for the here described implementation the connection is provided in two different ways: through a wired RS-485 communication bus using MODBUS protocols which centralizes the information in a local gateway which in its turn sends the information to an internet-based computing platform; or alternatively, through on-site transmitter that account for IoT (Internet of Things) cellular telecommunication modules. Such communication modules are based on Narrow Band technology and they allow to directly send the on-site read sensors/transmitters information to the server-based computing platform, without going through wiring and on-site internet accessibility facilities, factors that are always related to longer and more complex commissioning processes.

- *Computing Platform:*

[0033] Finally, the computing platform represents the core of the smart early detection system, as it is the component in charge of translating data (concentration readings, time, etc.) into leak information and the consequent notifications and alarms. Such reporting will prompt an early stage localization and repair of the refrigerant gas leak by the refrigeration system end-user or contractor, before important refrigerant losses are vented to the atmosphere. Beyond the computation of the refrigerant gas leak indicators (which represent the core of the present invention) the computational platform is also responsible for assessing the correct status of the refrigerant sensors/transmitters, registering the raw data, managing the notifications and alarms per transmitter, registering refrigerant gas leak information and auditing leak actions: namely time of detection, time of repair and details about the leak repair that might become meaningful for maintenance processes, such personnel involved, cause of the leak and actions that were taken. Depending on the embodiment the computing platform is placed locally (pc-based) or remotely (internet server-based), or is distributed between local and remote computing entities.

[0034] The computing platform is also able to triangulate the refrigerant gas leak information of several gas sensors/transmitters of their corresponding set that share a common volumetric surrounding in order to locate the refrigerant leak, as explained above, for example by using any of the Indoor Positioning System (IPS) available nowadays and/or a manual positioning system parameterized throughout the commissioning of the system by using standard position techniques: *x,y,z.*

[0035] Such computing platform is also preferably able to communicate the generated information (indicators, statistics, plots, etc.) to multiple stakeholders of the refrigeration system through several telecommunication technologies and devices, stating: position, probable leak time and severity of the leak in first term, besides standard safety alarms, among other indicators.

- *System performance:*

[0036] The principle of operation is as follows: a network of NDIR transmitters is deployed around the refrigeration apparatus, placing transmitters in the volumes with higher probability of leakage: compressor rooms, cold-rooms and/or above cold-rooms ceilings, refrigerated cabinets, liquid lines (usually in reduced volume ceilings) and condensing units. A good compromise between leak probability detection and acquisition cost might be between 10 and 25 sensing points for a standard supermarket, for instance.

[0037] When the sensors/transmitters are commissioned along with the system, the system parameterizes, among others aspects, the following meaningful information per transmitter:

- The volume of the zone surrounding the sensor/transmitter monitoring area (or typical standard size of its respective facility under commercial, industrial or transportation refrigeration, i.e. large cold-room; small refrigeration truck, etc.).
- Whether the sensor/transmitter shares a volume with some other sensor(s)/transmitter(s) (for instance in large and very large cold room with several evaporators).
- The total amount of refrigerant of the refrigeration system where the transmitter is installed.

[0038] The computing platform receives the readings of the sensors/transmitters (located at different locations of the refrigeration system) at a given frequency, which is smaller than 1 hour, and performs the above described computing of leak indicators and leak location.

[0039] Specifically, when a refrigerant gas leak takes place, a change of concentration is detected by the closest transmitter and/or transmitters, which sends the information to the computing platform. When the leak is confirmed by the computing platform an alarm or notification is sent, together with the respective leak indicators: severity (by modelling the leak intensity), localization (by triangulation when possible, as further detailed) and probable leak time, in the case the leak presents some time pattern related to specific refrigeration processes. As seen, all three indicators provide meaningful information for the early repair: where, when and how severe is the leak (weight of refrigerant or mass that is lost to the atmosphere).

[0040] The above mentioned explanation and equational developments leading to the above described equations of the method of the first aspect of the present invention are provided below, starting first by explaining the fundamentals and modelling of the refrigerant gas leak and continuing with the description of the computational models for the refrigerant gas leak indicators identified in a previous section.

Refrigerant gas leak fundamentals & modelling:

- *Gas concentration modelling for industrial applications:*

[0041] When a refrigerant gas leak takes place, refrigerant molecules expand around the refrigeration apparatus such that refrigerant concentration in the surrounding volume is present. How the concentration (hereafter c) of refrigerant evolves in space and time in such control volume is defined by a classic convection-diffusion equation, i.e. equation 1:

$$\frac{\partial c}{\partial t} = \nabla \cdot (D \nabla c) - \nabla \cdot (\vec{v} c) + L \qquad \text{(Eq. 1)}$$

Where t is time, D is the diffusivity of the refrigerant concentration, *vector v* is the velocity field and L is the source of refrigerant concentration (i.e. leak). For example, numerical simulations using CFD techniques are able to solve this transport equation (together with coupled mass and momentum conservation) and therefore predict the refrigerant concentration within the volume once leak and boundary conditions for the computational domain are known. Obviously, numerical simulations are not a practical nor feasible approach for the current industrial problem in consideration, as computing power and especially modelling of the boundary conditions are not applicable in a general way. However, from the fundamental equation it is indeed possible to observe that the evolution of the concentration in time (left hand side of the equation 1) depends on the equilibrium of the diffusion part, the convective part and the source term, i.e. the refrigerant gas leak in the case of the transport of refrigerant species. Then, for a steady state $\left(\frac{\partial c}{\partial t} = 0\right)$, an equilibrium between the source, the diffusive and the convective part is reached for any given control volume. Then, one could derive a much simpler equation by applying the conservation of mass and the definition of concentration c as the volume occupied by the refrigerant over the total control volume (occupied generally by air) for the volume where the concentration is sensed, as stated by equation 2:

$$c(T) = 10^6 \int_0^T \frac{L(t) - A(c) - B(t,c)}{\rho V} dt \qquad \text{(Eq. 2)}$$

[0042] Being c the concentration in ppm assuming it is homogenous within all the control volume V, T the filtering/integration time, L the leak (in grams of refrigerant per hour: g/h) function of time, A the diffused mass of refrigerant through seals of the volume (in g/h), B the out-vented mass of refrigerant through openings and velocity fields of the volume (traffic, in g/h), ρ the density of the refrigerant (in g/m^3) and, as said, V the analysis volume (in m^3). This much simpler equation retains the essence of the convection-diffusion equation (Eq.1) and allows to work with leak intensity as the mass of leaked refrigerant per hour in the volume V, as long as terms A & B are modelled depending both on the concentration (the diffusive and convective fluxes are bigger for higher concentrations) and on the time (as term B might not be constant due to traffic in the volume, ventilation processes, etc.). As it will be described in next section, a way to statistically correlate concentration and leak intensity is to model terms A & B for different reference concentrations c and volumes V (c_{ref} and V_{ref}). Hence, when a statistical steady-state concentration c is reached for a volume V, the leak can be approximately estimated from the diffusion-convection modelled terms A & B, with corrections when needed, as further detailed.

Computational model for leak indicators:

[0043] As previously explained, the early detection of the refrigerant gas leak captured by the on-site transmitters require of leak indicators for an efficient management, quick localization and repair. The calculations of the leak indicators are performed at the computing platform, as computing power and some system considerations are needed. This section will present the technical basis for the TGCI (Time-Gas Concentration Index) as a leak time indicator, the LPI (Leak Potential Index) and the LCI (Leak Charge Index) as leak severity indicators and, finally, the coordinates LX, LY and LZ, i.e. leak coordinates or leak predominant coordinate, when applicable.

- TGCI: Leak Time indicator:

[0044] Experience shows that several refrigerant gas leaks take place at precise moments of the refrigeration process, for example activation of Hot-Gas valves in defrost systems. Therefore, refrigerant concentration reaching steady-state for some short hours during the day, as after the process is finished, concentration tends to decrease again, as per equation 2 (being L=0). The leak final localization and repair must be done when the specific leaking process is taking place, sometimes at unavailable man-hours. The TGCI is an indicator performed on hourly averages during several days (calendar on demand), indicating the concentration average per hour, hence showing the most probable hour for the leak to take place, should the leak not be constant in time. The TGCI is displayed as a histogram for 0-24h, as depicted in Figure 1(a), which indicates when the leak inspection, final localization and repair should be planned.

- LPI & LCI: Leak Severity Indicators:

[0045] After the leak concentration model described above has been obtained, the computing platform is able to estimate leak severity when terms A & B are modelled and the approximate volume of the application V is specified (it is therefore needed to define the corresponding volume of detection for each on-site transmitter during commissioning). As said, the computing platform reads and registers the refrigerant concentration at a defined monitoring frequency. Once a statistical averaged concentration c is reached (as filtered by the platform), the transient term of equation 1 vanishes, therefore obtaining the following relationship for the leak (equation 3):

$$\overline{L(T)} = \frac{1}{T}\int_0^T A(t,c) + B(t,c)dt \qquad \text{(Eq. 3)}$$

Where T, as previously explained, is a finite filtering/averaging time such that average concentration c is approximately constant in the period of time T, as assessed by the platform. As the reader may guess, such approach would need a modelled database of the terms A & B for any (infinite) volumes V and concentration c, as these two application values can be *a priori* any real number. In order to produce a manageable computational system, several terms for A & B pairs can be modelled at different (definite) volumes and concentrations V_{ref} and c_{ref}, the system correcting the final leak indicator L with the closest values of reference (V_{ref}, c_{ref}) with respect the real application values (V, c) after equation 4:

$$\overline{L(T)} = \frac{c}{c_{ref}}\frac{V}{V_{ref}}\frac{1}{T}\int_0^T A(t,c_{ref}) + B(t,c_{ref})dt \qquad \text{(Eq. 4)}$$

[0046] This linear correction allows to extrapolate the modelled values of A & B defined for concentration c_{ref} when the on-site reading concentration c is of the same order of magnitude; the same reasoning applying for the volume V. Modelling of A & B pairs can be done both numerically and experimentally for multiple standard volumes in commercial and industrial refrigeration systems (ranging from few litters for refrigerated cabinets to thousands of m^3 for industrial cold rooms) and at different concentration levels. Modelling of the parameters A & B for several refrigeration applications is not disclosed in this patent.

[0047] Once the averaged refrigerant gas leak L is computed (in g/h), the Leak Potential Index (LPI) is computed as the estimation of leaked kg refrigerant per year or, alternatively, tons of CO_2 per year, making use of the GWP of the refrigerant of the system (if parameterized at the computing platform) assuming that the computed leak will remain unattended and constant throughout the year. This indicator allows to assess the severity of the leak from both economic and environmental points of view if left unattended and, therefore, manage its priority in terms of on-site inspection and repair. Additionally, a second severity indicator, the so-called Leak Charge Index (LCI), is computed at the platform. This index is obtained by dividing the yearly estimated leak (LPI in kg/year) by the total charge of refrigerant of the installation (kg), hence stating the % of refrigerant system loss that will be produced by the detected refrigerant gas leak, if left unattended. The LPI and the LCI indicators are displayed as a number by the system, as depicted in Figure 1(b). It is important to mention that computing the severity of the leak from the concentration reading is essential for the industry, as the effects of the leak on the concentration are clearly not linear and, therefore, the concentration reading is not a good indicator -sometimes even misleading- to acknowledge the leak severity.

- LX, LY and LZ: Leak coordinates:

[0048] An important refrigerant gas leak early detection support indicator is the triangulation of the leak coordinates based on several concentration readings from different transmitters. As the reader may infer, when only one transmitter is placed in a volume *V*, such triangulation process is not possible, being the spatial coordinates of the on-site transmitter the best guess for the leak coordinates. On the other hand, when several transmitters share a generally extended volume (for instance, an industrial cold room or a suspended ceiling), the different time-concentration behaviour of the transmitters can be used to estimate the leak position, making use of the transient term of the refrigerant leak modelling defined above.

[0049] Therefore, the computing platform requires the spatial coordinates (*x*, *y*, *z*) for all system transmitters (coordinates defined either by Indoor Positioning Systems IPS or manually, together with user-defined reference coordinates at the commissioning of the system). Additionally, the computing platform requires tagging sets of neighbour transmitters, for those that share a volume *V* (neighbour tagging also performed during commissioning).

[0050] With this information, right after any of the set transmitters detects a refrigerant concentration change, the computing platform assigns a count-down decreasing time t_{leak} to all neighbourhood set of transmitters. The leak time-stabilisation concentration for each transmitter (*n*), is computed as shown in equation 5:

$$TC^n = \left(t_{leak}c\right)^n = t_{leak}^n \cdot \overline{c^n} \qquad \text{(Eq. 5)}$$

[0051] Being *n* an index defining each transmitter (ranging from *1* to *N*) and t_{leak} the count-down time for the neighbour set of transmitters. Once a steady-state concentration *c* is reached for each transmitter of the set, the respective time $t^n{}_{leak}$ (count-down time required for the concentration to reach such steady-state by transmitter *n*) is used to compute the leak time-stabilisation concentration *TC* for each transmitter, as explained by equation 5. Hence, the last transmitter of the set to reach a stable concentration will present a smaller leak-time than those closer to the leak (as leak-time is a decreasing but positive number). High leak time-concentration values will be associated to closer positions to the refrigerant gas leak (higher concentration and faster leak-time), while low leak time-concentration values are typical of further positions with respect to the leak (lower concentrations and slower leak-time).

[0052] When all leak time-concentration values have been obtained for the set of transmitters, the system correlates such values with the respective *x, y* and *z* transmitter coordinates. A polynomial regression model is then applied using the method of least squares, although similar techniques such splines can be used. For instance, for the leak-x-dependence modelling, a polynomial $TC^{fit}(x)$ is fitted to the points composed by the actual time-concentration values *TC* and their respective x-coordinate per set (generally from *x(1)* to *x(N)*, *N* being the transmitters of the neighbour set, i.e. sharing volume *V*), as described by equation 6:

$$TC^{fit}(x) = \beta_0 + \beta_1 \cdot x + \ldots \beta_n \cdot x^n \qquad \text{(Eq. 6)}$$

[0053] The regression model provides the polynomial $TC^{fit}(x)$ that produces the minimum least squares with respect the actual values of *TC(x).* Depending on the number *N* of available correlation points, different polynomials can be obtained (linear, cubic, etc.). If an acceptable correlation is obtained (coefficient of determination $R^2 > 0.6$) for any of the three polynomial fittings performed ($TC^{fit}(x)$, $TC^{fit}(y)$, $TC^{fit}(z)$) a maximum analysis of each fitted polynomial -per coordinate- can be carried out, as shown by equation 7 for the x-coordinate:

$$LX = leak(x) = MAX\left[TC^{fit}(x)\right]_{x(1)}^{x(N)} \qquad \text{(Eq. 7)}$$

[0054] If a maximum of the function is within the physical transmitters coordinates (in equation 7: *x(1)...x(N)*), the leak coordinates (*LX, LY, LZ*) are obtained as coordinates for maximum *TC.* It is important to mention that if the function does not present a maximum within the physical coordinates (as for example if a linear polynomial is obtained for *TC* with *N*=2) a leak preferred orientation can be derived from the analysis, i.e. increasing or decreasing *x* with respect to transmitter *n.*

[0055] Some application examples of the present invention are provided below, in order to clearly demonstrate the importance of the invention and particularly of the different indicators provided thereby, and also of the location of the refrigerant gas leaks.

LPI & *LCI indicators:*

[0056] First, the importance and application of the severity leak indicators LPI & LCI, particularly for refrigeration stakeholders, will be described below, starting by describing its background.

[0057] Refrigerant gas detection has historically worked with Particles Per Million (ppm) as measuring unit because toxic effects (related to refrigerant gas on human beings) depend on the concentration (ppm) level only. Hence, gas detectors are built based on measuring/alerting/reacting depending on ppm. Detectors measure the concentration of refrigerant within a volume around (and outside) the refrigeration system, alerting when the volume is not safe for people. One could say that gas detectors measure the consequence of the leak in the air surrounding the system (concentration of refrigerant diluted in air), but they never measure the severity of the cause of the leak in operational and business terms (mass of refrigerant gas leaked per hour or kg/year) that causes such concentration in the surrounding volume.

[0058] Therefore, refrigeration stakeholders ideally would need two different numbers to make decisions:

- Refrigerant concentration (ppm) for personnel safety aspects (for HFC refrigerants generally above 10 000 ppm).
- The severity of the leak (g/h or kg/year or %charge/year) for maintenance, operational, economic and environmental aspects. Is the leak urgent? Can repairing wait? Are there more urgent leaks?

[0059] While the former (ppm) is given for standard systems (safety of the area), no information about the latter (severity of the leak) is given by any direct refrigerant gas detection system or product known in the prior art. Precisely, the present invention describes a method to correlate concentration and severity of the leak.

[0060] The indicators LPI (Leak Potential Index) and LCI (Leak Charge Index), as described above, measure the severity of the refrigerant gas leak, therefore give answer to the technical problem that refrigeration stakeholders are facing nowadays.

Application examples for LPI&LCI:

EXAMPLE 1:

[0061] In order to illustrate the performance of the system, the LPI and LCI indicators obtained by the commercial realization of this smart early detection system are presented. The concentration reading displayed in Figure 2 was obtained in a 30 m^3 cold room of a supermarket in Madrid (Spain) between 5th and 14th May 2018. This supermarket presented high leak rates for the last years (above 90% of the nominal refrigerant charge was refilled every year) and the deployment of the smart early detection system consisted in monitoring compressor room, 4 different cold-rooms, 7 refrigerated displays and the condenser unit.

[0062] As seen in Figure 2, the concentration oscillates (as per the refrigeration cycles inside the evaporator of the cold room) but shows a clear stable behaviour around 53 ppm. The smart early detection system immediately identified the leak after commissioning (as the leak existed before the deployment of the detection system). The smart early detection system, after the initial two hours, provided leak severity indicators, as modelling values for the mean time integral of terms $A + B$ ($1/T(\int A + Bdt)$) were available from experimental and numerical tests, as shown in table 1.

Table 1. Computing values for the LPI indicator (equation 4)

V_{ref} (m^3)	C_{ref} (ppm)	$1/T\int Adt$ (g/h)	$1/T\int Bdt$ (g/h)	$V_{cold\ room}$ (m^3)	$C_{cold\ room}$ (ppm)	*LPI* (kg/year)
7	67	1.45	0.21	30	53	49.29

[0063] Hence, after equation 4 (linearly correcting both concentration and volume), the leak is computed as 5.62 g/h, being the LPI (Leak Potential Index) of 49.29 kg/year and the LCI (Leak Charge Index) of 35.2%, as the system accounted for 140 kg nominal refrigerant charge. This is to say, the leak detected in the cold room, if left unattended, would cost around 50 kg of refrigerant per year, causing the loss of approximately one third of the total refrigerant charge annually. The supermarket owner, once obtained such information, had no doubts to replace the perforated evaporator in the following 10 days of the detection, despite the very low value of refrigerant concentration: 53 ppm.

[0064] From an economical and operational points of view, this information becomes fundamental for the decision-making process. Indeed, after the warning was triggered by the system, the maintenance team revised the evaporator of the cold-room and observed that the evaporator was perforated. The owner of the installation doubted at first whether replacing the evaporator or not, as the concentration was very low, and the related costs of replacing the evaporator were around 1000 € (700 € new evaporator, 300 € replacement man-hours). Thanks to the computed indexes (LPI around 50 kg/year; LCI=35%), a refill of around at least 50 kg was needed by the refrigeration system every year (the refrigeration system accounted for 140 kg nominal charge, becoming non-operative under 100 kg). As per current cost of the refrigerant R404A (150 €/kg, including taxes) and based on the LPI and LCI indicators, the owner had an easy decision to make, as the cost of the estimated leak was around 7750 € annually, including man-hours for the refrigerant refilling. The evaporator replacement was then finally carried-out, saving around 6500 € in the current year.

EXAMPLE 2:

[0065] A detection system in a supermarket presents 3 sensors with readings different from 0 ppm (0 ppm is the expected reading when no leak is present). Therefore, the maintenance team asserts that 3 leaks are detected.

- Leak A (147 ppm) in a refrigerated display 2.5 m long (0.3 m^3)
- Leak B (23 ppm) in a compressor room (300 m^3)
- Leak C (248 ppm) in a refrigerated display 10 m long (4 m^3)

[0066] The maintenance team is not able to prioritize which of the leaks is more urgent, if any, based on the concentration readings. The LPI indexes show the following information: Leak A (12 kg/year), Leak B (87 kg/year), Leak C (112 kg/year). After such analysis, the maintenance team decides to urgently address only leaks B and C, which are causing a big deficit of refrigerant per hour. Leak A is kept under surveillance and most likely, the refrigerated display will be replaced only if LPI exceeds 20 kg/year.

EXAMPLE 3:

[0067] A concentration reading is obtained in an industrial cold room of 5000 m3. A very low concentration is obtained (12 ppm) only during 8 h per day. The owner thinks that the leak is insignificant as it is not constant nor high concentration is reached. The LCI indicator however, after averaging concentration along the day (4 ppm) and for the volume in consideration returns 178 kg/year (around 25 000 € / year). With this information, inspection and repair is launched, despite the extremely low concentration read.

EXAMPLE 4:

[0068] A supermarket small cabinet (with total cost of 300 €) is showing a concentration of 234 ppm in average. Repair is not possible, although the owner hesitates to replace the cabinet as the cost of the leak is unknown. However, the LPI (36 kg/year) shows that the cost of keeping the cabinet (refrigerant R134A at 100 €/kg) is about 10 times the price of the cabinet itself (per year), so replacement is mandatory.

EXAMPLE 5:

[0069] A refrigeration contractor is in charge of the maintenance of 10 supermarkets in Barcelona. All supermarkets have a smart refrigeration detection system, centralized in a computing platform in the "cloud" (internet server). On Monday one warning based on the concentration of a cold-room in supermarket 1 is obtained at 34 ppm. At the same time, a refrigerated display in supermarket 8 indicates 201 ppm. The contractor only has two available technicians and needs to decide to which supermarket address first, if any. The LPI of the leaks are of 9 kg/year in supermarket 1 and 11 kg/year in supermarket 8, so similar values. On the other hand, the LCI for supermarket 1 is 3 % (300 kg of nominal charge) while the LCI for supermarket 8 is 110%, as the supermarket is very small and the refrigerant nominal charge is 10 kg. The contractor, based on this information, understands that the leak in supermarket 8 is relatively more important and needs to be addressed quickly, as every week the refrigerant charge drops by more than 2% of the total refrigerant charge, i.e. the same than the refrigerant gas leak during all year long for supermarket 1, which can be addressed next month when technicians are planned for regular maintenance work (as in 1 month only 0.25% of total system charge will be leaked).

Location of the refrigerant gas leak:

[0070] Here, the importance and application of determining the location of the refrigerant gas leak, particularly for refrigeration stakeholders, will be described, also starting by describing its relevant background.

[0071] Refrigeration systems have historically leaked big amounts of refrigerant because a complete leak-tight system is very difficult to achieve (as the refrigeration system is composed by multiple moving parts) and, moreover, it is not static, i.e. a completely leak tight system (as delivered in day 1) might start leaking in day 2 again due to vibration, corrosion and other factors related to the aging of the system, without any kind of accident. Besides, HFC refrigerants are colourless and odourless so detection is extremely difficult. In order to avoid refrigerant gas leaks, frequent leak inspection processes are needed to ensure the system is free of leaks. Such processes are generally not carried out by the industry, as per related cost of technicians and the big amount of hours that are needed to inspect systems with hundreds of meters of piping, dozens of evaporators and multiple compressors, valves, brazed elements, etc. Even when a leak is detected (as per refrigerant low level in the system refrigerant reservoir) the inspection of the system generally does not encounter the responsible leak, as it is very difficult to focus where to perform the exhaustive inspection without any tip on leak location.

[0072] The use of several high sensitive transmitters in extended areas/volumes of the refrigeration system can enormously help to estimate the coordinates of the leak origin. By knowing the coordinates of the leak origin, the time needed for leak repair might be reduced exponentially, as the area left for inspection is reduced only a few meters around the estimated coordinates.

Application examples for leak location:

Example A:

[0073] With reference to Figure 7 and Table 2, an example, used for illustrative purposes, concerning how the present invention locates the refrigerant gas leak is here described.

[0074] As shown in Figure 7, the system comprises four sensors/transmitters (A, B, C and D) which share a volume, being sensors/transmitters B and C inside a second area surrounded by walls but yet sharing a common volume with sensors/transmitters A and D. When commissioning the system, sensors/transmitters A, B, C and D have been related to a neighborhood set of sensors/transmitters. Sensors/transmitters are located in different points of the shared volume, defined by coordinates x,y,z, as shown below:

Sensor/Transmitter	Coordinates		
	x	y	z
A	0	0	-10
B	10	0	0
C	20	0	0
D	30	0	10

[0075] Table 2 below shows the refrigerant concentration per sensor/transmitter with respect to absolute time obtained from the sensors of Figure 7.

Table 2

	Concentration (ppm)			
Time (s)	Sensor A	Sensor B	Sensor C	Sensor D
0	0	0	0	0
120	0	0	0	0
240	0	0	0	0
360	0	0	5	0
480	0	0	25	0
600	0	0	30	0

(continued)

	Concentration (ppm)			
Time (s)	Sensor A	Sensor B	Sensor C	Sensor D
720	0	0	40	0
840	0	0	50	0
960	0	0	60	0
1080	0	0	60	0
1200	0	0	60	5
1320	0	0	60	10
1440	0	5	60	20
1560	0	10	60	30
1680	0	15	60	40
1800	0	20	60	50
1920	0	25	60	50
2040	0	40	60	50
2160	0	40	60	50
2280	0	40	60	50
2400	0	40	60	50
2520	0	40	60	50
2640	0	40	60	50
2760	0	40	60	50
2880	0	40	60	50
3000	5	40	60	50
3120	10	40	60	50
3240	20	40	60	50
3360	20	40	60	50
3480	20	40	60	50
3600	20	40	60	50

[0076] Figure 8 shows the time evolution of the 4 sensors/transmitters of the neighbourhood set of Figure 7, while Table 3 below shows the time concentration per sensor/transmitter with respect to leak time, defined by sensor/transmitter C (the first one to detect a concentration change, for this example). The marked cells contain the values that define that a steady-state is reached by each sensor/transmitter.

	Time-Concentration (ppm-s)			
Decreasing Time relative to leak	Sensor A	Sensor B	Sensor C	Sensor D
0	0	0	0	0
0	0	0	0	0
0	0	0	0	0
3600	0	0	18000	0
3480	0	0	87000	0
3360	0	0	100800	0
3240	0	0	129600	0
3120	0	0	156000	0
3000	0	0	180000	0
2880	0	0	172800	0
2760	0	0	165600	13800
2640	0	0	158400	26400
2520	0	12600	151200	50400
2400	0	24000	144000	72000
2280	0	34200	136800	91200
2160	0	43200	129600	108000
2040	0	51000	122400	102000
1920	0	76800	115200	96000
1800	0	72000	108000	90000
1680	0	67200	100800	84000
1560	0	62400	93600	78000
1440	0	57600	86400	72000
1320	0	52800	79200	66000
1200	0	48000	72000	60000
1080	0	43200	64800	54000
960	4800	38400	57600	48000
840	8400	33600	50400	42000
720	14400	28800	43200	36000
600	12000	24000	36000	30000
480	9600	19200	28800	24000
360	7200	14400	21600	18000

Table 3

[0077] While Table 4 below shows the steady-state time-concentration values for further polynomial adjustment in order to determine de leak coordinates.

Table 4

Transmitter/Sensor	Coordinates			Steady-state reached at relative time (s)	Time-concentration at steady-state (ppms)
	x	y	z		
A	0	0	-10	480	9600
B	10	5	0	1680	67200
C	20	0	0	2760	165600
D	30	0	10	1920	9600

[0078] When plotting the stabilized time-concentration values with respect to the three-coordinates, the curves shown in Figures 9, 10 and 11 are obtained (Figure 9: x-dependence, Figure 1010: y-dependence, Figure 1111: z-dependence).

[0079] With the following adjusted polynomials:

DIRECTION	Adjusted Polynomial	R^2	Meaningful?(R^2>0.5)	Max position
x-dependence	$-34,8x^3+1248x^2-3240x+9600$	1	YES	X=22.561
y-dependence	-4640y+90400	0.032	NO	N/A
z-dependence	$-636z^2+4320z+116400$	0.6163	YES	Z=3.390

[0080] Therefore, for the here described example the refrigerant gas leak is around the coordinates X=22.561 and Z=3.390 (coordinates that indicate maximum values for the adjusted polynomial along the respective directions) with respect to the origin of coordinates. There is no information around the position Y, as no meaningful correlation is obtained. The leak position is displayed by Figure 12.

EXAMPLE B:

[0081] The refrigerant piping of a hypermarket is placed above a ceiling. The ceiling covers all the surface of the hypermarket (10 000 m2). The amount of piping and valves in such area is very important (hundreds of meters of piping and dozens of valves to feed the evaporators of cold-rooms and refrigerated cabinets/displays of the hypermarket). The inspection of this area is very difficult, as the piping is suspended from the ceiling and there is no easy access to the area.

[0082] If no detectors are installed in the hypermarket, a refrigerant gas leak require an inspection of the whole system, inch by inch.

[0083] If there is only one HFC detector in the ceiling, when a leak takes place and it is detected, all piping (inch by inch) and valves of the ceiling need to be checked prior to final location and repair.

[0084] On the other hand, when using 6 HFC transmitters distributed all over hypermarket ceiling area allows triangulation of the refrigerant gas leak, as explained above according to the method of the first aspect of the invention, such that technicians can start leak inspection around coordinates LX, LY, LZ and detect the piping hole within minutes, instead of hours (only when using one detector) or days (without any detection system).

EXAMPLE C:

[0085] A logistic centre of a supermarket chain has 6 industrial cold-rooms of 5000 m3 average each. The total charge of refrigerant of the system is 1900 kg of R448A. The owner installs a smart detection system in the logistic centre using only 6 transmitters (one per cold-room). A leak take places on top of cold-room 3 causing 4 out of the 6 transmitters to detect concentration. The triangulation of the leak and the positioning of the gas detectors at different coordinates (length x, wide y and high z) allows to locate the leak in the above cold room area of cold room 4. The location estimation allows to repair the leak in a time lapse of 4 hours, saving the inspection of hundreds of meters of piping and also saving around 15 kg of refrigerant, as the leak was very intense (3400 kg/year = 0.4 kg/h). It is important to note that such leak would have implied 20 kg of refrigerant (1400 €) if the leak location had required a minimum of 2 days (without the help of triangulation) or 49000 € (700 kg leaked before the system had lost cooling capacity) without a detection system.

[0086] Further preferred embodiments of the present invention are described below with reference to Figures 3 to 6.

PREFERRED EMBODIMENT 1

[0087] Figure 3 describes the local installation of the gas sensors/transmitters. Figure 4 schematically illustrates the system of the invention applied to the described (Figure 3) commercial refrigeration system (supermarket); which comprises a set of 9 NDIR-based R134a refrigerant transmitters, a wiring bus (based on MODBUS protocols) and a local computing platform. Each refrigerant transmitter is composed by a highly sensitive autonomous Non Dispersed Infra-Red (NDIR) gas sensor and a transmitter, i.e. a filtering/communicating device that reads the sensor, filters the signal and eventually communicates to the computing platform through a wired MODBUS engineered communication channel.
[0088] The computing platform is able to assign a set of parameters for each transmitter (such as although not limited to):

- volume where the transmitter is placed (i.e. cold room of 20 cubic meters, compressor rack room of 100 cubic meters, etc.)
- area typology (refrigerated cabinet, cold room, machinery room, outdoors, etc.)
- 3D position in geolocation (precision of +-1 m) using either
    - Indoor Positioning Systems (A-GPS; or using anchors as nodes with known positions, e.g. WiFi access points or Bluetooth beacons)
    - Manual entry of coordinates (x,y,z) of the transmitter with respect to a coordinate system referred to the refrigeration apparatus.
- refrigerant gas to sense
- date of commissioning
- etc.

[0089] The computing platform can also accept general parameters that define general aspects for the set of sensors/transmitters of the system (group tags) what can be useful for statistical analysis relating different installed systems.

- refrigeration system typology (commercial refrigeration, industrial refrigeration, transport refrigeration, etc.)
- area of installation (cold room, refrigerated display, compressor rack room, etc.)
- contractor in charge
- end user/property
- economic cost for the end-user/property of the refrigerant in consideration in the installation(s) in consideration

[0090] Once the specific and general parameters of the system are described at the computing platform, the system performs as follows:

Principle of operation:

[0091] As stated in a previous section, the present invention proposes a system able to detect refrigerant leaks at early stages (low, moderate refrigerant mass flow rates of the order of grams per hour), estimate location and most probable time to locate the leak, register data, quantify, categorize and prioritize the leak severity.
[0092] For that, any sufficiently important refrigerant leak located in the surrounding area of the sensor/transmitter will trigger either a concentration reading and/or a change of the concentration reading of the sensor/transmitter. Once a concentration reading or its respective change are detected and real-time communicated to the computing platform, a calculation relating the concentration reading, the change in time of the concentration reading and the volumetric area assigned to the sensor/transmitter will be translated to an estimation of the refrigerant mass flow (grams/hour) happening in the sensor/transmitter surrounding area thanks to a model that will be described further down. This information will be automatically transformed into kg/year to leak (if leak unattended) what is the so-called LPI (Leak Potential Index). The LPI allows to the stakeholder to clearly understand the severity of the leak and to categorize its priority to be finally located and repaired. Indeed, given the economic cost of the refrigerant gas and its GWP (Global Warming Potential), an estimation of economic cost of the leak and the equivalent CO_2 tons, among other parameters, is associated to the leak (€/year, eq. tons CO_2/year, etc.). As said, specifics about the computation of this index are detailed further down.
[0093] Still related to the system performance, a second important indicator is the so-called TGCI (Time-Gas Concentration Index). The TGCI is an indicator that distributes concentration readings hourly, daily or weekly (as parameterized by the system user) such that it can correlate the most probable hour/day/week to locate the leak, in the case it is not constant in time (which is the case in the most complex refrigerant leaks, happening only under very specific refrigeration system maneuvers). The index is presented as a histogram for 0-24h, 1-7 days of the week and 1-31 days of the month. Specific computation of the index is detailed further down.

[0094] The computing platform also relates the indicators of all sensors/transmitters in real time as those could be related to the same refrigerant leak and/or different leaks happening at the same time. Based on the location information for each sensor/transmitter (provided by either an Indoor Positioning System, which is out of the scope of this patent, or by a manual entry of position coordinates: xyz), an algorithm can linearize up to 3 dimensions the concentration reading and the concentration change in time associated to each affected sensor/transmitter and decide either the same leak is responsible for the outputs or multiple leaks are taking place simultaneously. The specific way to triangulate the location is also detailed further down.

[0095] Based on these indicators (severity, location and time), the computing platform triggers alarms that are sent through several telecommunication platforms to the stakeholders of the refrigeration system.

PREFERRED EMBODIMENT 2

[0096] While applying to the same commercial refrigeration system described by Figure 3, Figure 5 schematically illustrates the system of the invention which also comprises a set of 9 NDIR-based R134a refrigerant transmitters T1-T9, in this embodiment connected through Narrow Band cellular (wireless) internet telecommunication technology to an internet server (internet server hereafter referred as "cloud"). As for embodiment 1, Each refrigerant transmitter is composed by a highly sensitive autonomous Non Dispersed Infra-Red (NDIR) gas sensor and a cellular transmitter, i.e. a filtering/communicating device that reads the sensor, filters the signal and on-demand communicates to the computing platform (at cloud) through Narrow Band cellular (wireless) internet telecommunication technology provided by commercial telecommunication operators.

[0097] A slight variation is shown in Figure 6, for which the 9 NDIR-based R134a refrigerant transmitters are connected through a Wi-Fi based network to a computing platform at cloud via a local computing platform and/or a bridge or gateway.

Principle of operation:

[0098] The principle of operation is identical as the preferred embodiment 1, interchanging the way transmitters are connected to the computing platform. As in preferred embodiment 1, once a sufficient concentration reading and/or a sufficient concentration change is detected, a communication can be forced to the cloud (or just registered, depending on the communication specifications as defined by the user), where the computing platform receives the information and performs the computations and delivers the indicators. This aspect must be underlined with respect to the preferred embodiment 1, where communication is continuously held through a wired bus in real time. Here communication can be customized by the user, for example transmitting only when needed (potential leak detected) or following a regular frequency. Precisely, for the preferred embodiment 2, an additional functionality is based on the user-defined characterization of the communication policy between transmitters and computing platform ("cloud"), as communication can be specified regularly (once per minute, per hour, per day, etc.) while all collected events and reports are communicated at once; or communication can be specified as regular but forcing special transmissions in case of warnings, and/or pre-alarms and/or alarms; and/or combinations of the two scenarios (only regular transmission frequency or only event-triggering transmissions).

[0099] A person skilled in the art could introduce changes and modifications in the embodiments described without departing from the scope of the invention as it is defined in the attached claims.

Claims

1. A computer implemented method for monitoring refrigerant gas leaks in a refrigeration system, comprising:

- detecting a refrigerant gas leak within a predetermined volume and measuring, along time, a concentration of said detected refrigerant gas leak within said predetermined volume; and
- estimating the severity of said detected refrigerant gas leak by computing a leak severity indicator that relates said concentration measurements to refrigerant gas leak intensity represented by estimations of mass leaked over time within said predetermined volume.

2. A method according to claim 1, comprising computing said leak severity indicator based on a mass conservation model that relates concentration values to refrigerant gas leak intensity, within a volume, density of the refrigerant gas, and modelled diffusion and convection terms, A and B, of the refrigerant gas which leaves said volume.

3. A method according to any of the previous claims, wherein said computing of said leak severity indicator comprises extrapolating the same from a plurality of modelled values for the mean time integral of said diffusion and convection terms, *A* and *B*, for a corresponding plurality of values of reference concentrations c_{ref}, and reference volumes V_{ref}.

4. A method according to claim 3, wherein said extrapolation is performed by computing the following equation:

$$\overline{L(T)} = \frac{c}{c_{ref}} \frac{V}{V_{ref}} \frac{1}{T} \int_0^T A(t, c_{ref}) + B(t, c_{ref}) dt$$

where *c* stands for the concentration measurements, *V* for the predetermined volume, *T* is a finite filtering/averaging period of time, $\overline{L(T)}$ is the refrigerant gas leak intensity averaged along *T*, and $A(t,c_{ref})$ and $B(t,c_{ref})$ are said diffusion and convection terms, *A* and *B*, for the reference concentration c_{ref} and reference volume V_{ref} to be integrated for a time *t* going from *0* to *T*.

5. A method according to claim 4, wherein said leak severity indicator is $\overline{L(T)}$, as the estimation of leaked refrigerant mass per hour.

6. A method according to claim 4, wherein said leak severity indicator is a Leak Potential Index (LPI) computed from $\overline{L(T)}$ as the estimation of leaked refrigerant mass per year, or the estimation of equivalent tones of CO_2 per year, assuming the leak is left unattended and constant throughout the following year.

7. A method according to claim 6, further comprising computing a further leak severity indicator which is a Leak Charge Index (LCI) obtained by dividing the Leak Potential Index (LPI), when expressing the estimation of leaked refrigerant mass per year, by the total charge of refrigerant of the refrigeration system.

8. A method according to any of the previous claims, further comprising locating the refrigerant gas leak by performing said detection and measuring step with several refrigerant gas detectors placed at different locations and forming at least one set of *n* refrigerant gas detectors configured and arranged for operating for said predetermined volume, and triangulating the refrigerant gas leak spatial coordinates from the concentration measurements provided by said several refrigerant gas detectors and the spatial coordinates thereof.

9. A method according to claim 8, comprising carrying out said triangulation based on the different time-concentration behaviour of the refrigerant gas detectors.

10. A method according to claim 9, comprising carrying out said triangulation by sequentially performing the following steps:

- detecting a refrigerant gas concentration change by means of any of said refrigerant gas detectors,
- assigning and starting a positive count-down decreasing time t_{leak} to at least all of said refrigerant gas detectors forming said at least one set;
- detecting, for each refrigerant gas detector *n*, that a concentration steady-state $\overline{c^n}$ has been reached for the refrigerant gas concentration measured thereby, and at that moment checking the value of the count-down decreasing time t_{leak}^n for the corresponding refrigerant gas detector *n*,
- obtaining the value of a time-stabilisation concentration variable TC^n for each refrigerant gas detector, by means of the following equation:

$$TC^n = (t_{leak} c)^n = t_{leak}^n \cdot \overline{c^n}$$

- correlating all the TC^n values obtained with the respective x, y and z refrigerant gas detectors spatial coordinates,
- applying a polynomial regression model to the obtained correlated points, to obtain at least three fitting polynomial $TC^{fit}(x)$, $TC^{fit}(y)$, $TC^{fit}(z)$, one per spatial coordinate, and
- performing a maximum analysis of each of the three fitting polynomial $TC^{fit}(x)$, $TC^{fit}(y)$, $TC^{fit}(z)$, and, from the results provided with said maximum analysis, determine that the refrigeration gas leak spatial coordinates are those which correspond to the ones for which said fitting polynomial $TC^{fit}(x)$, $TC^{fit}(y)$, $TC^{fit}(z)$ present a maximum, or, if no maximum is presented, the one for which a refrigerant gas leak preferred orientation is derived.

11. A method according to any of the previous claims, further comprising computing a leak time indicator expressed by means of a Time-Gas Concentration Index (TGCI) by hourly averaging during several days the measured refrigerant gas leak concentration.

12. A computer program, comprising program code instructions that when run in a computer or a processor implement the steps of the method of any of the previous claims.

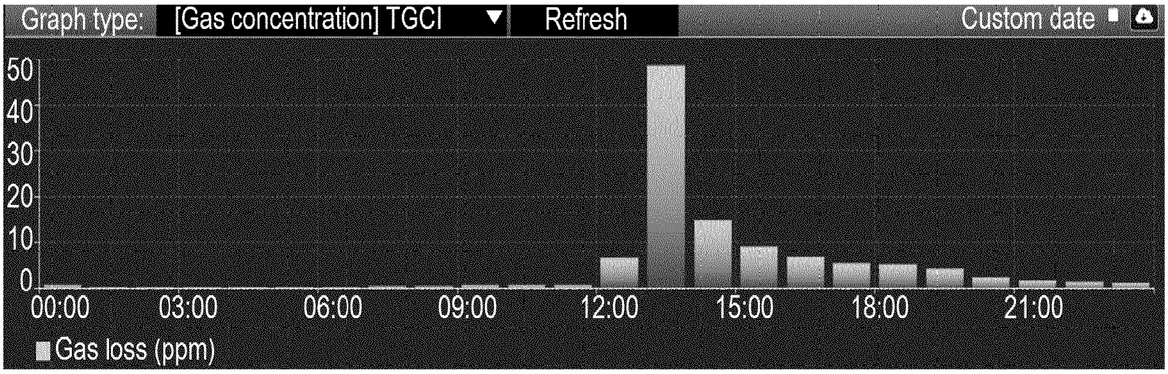
13. A system for monitoring refrigerant gas leaks in a refrigeration system, comprising:

- at least one refrigerant gas detector configured and arranged for detecting a refrigerant gas leak within a predetermined volume, measuring, along time, a concentration of said detected refrigerant gas leak within said predetermined volume, and providing corresponding electrical signals representative of the concentration measurements; and
- at least one computing entity configured and arranged to receive said electrical signals, retrieve data representative of said concentration measurements therefrom, and for process said data according to the method of any of claims 1 to 12.

14. A system according to claim 13, wherein said at least one computing entity comprises storage means for storing data representative of said plurality of modelled values for the mean time integral of the diffusion and convection terms, *A* and *B*, and of the corresponding plurality of values of reference concentrations c_{ref}, and of the reference volumes V_{ref}, and wherein the at least one computing entity is adapted to process said stored data to extrapolate the leak severity indicator therefrom according to the method of claim 3 or of any of claims 4 to 11 when depending on claim 3.

15. A system according to claim 13 or 14, comprising a graphical user interface (GUI) operatively connected to said computing entity (C) to graphically display values obtained for said leak severity indicator, said further leak severity indicator, and/or said leak time indicator.

(a)



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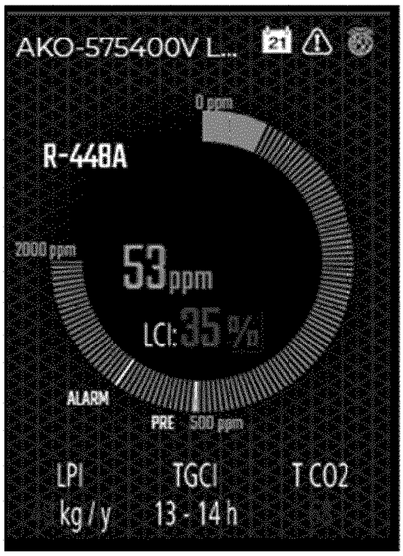


Figure 1

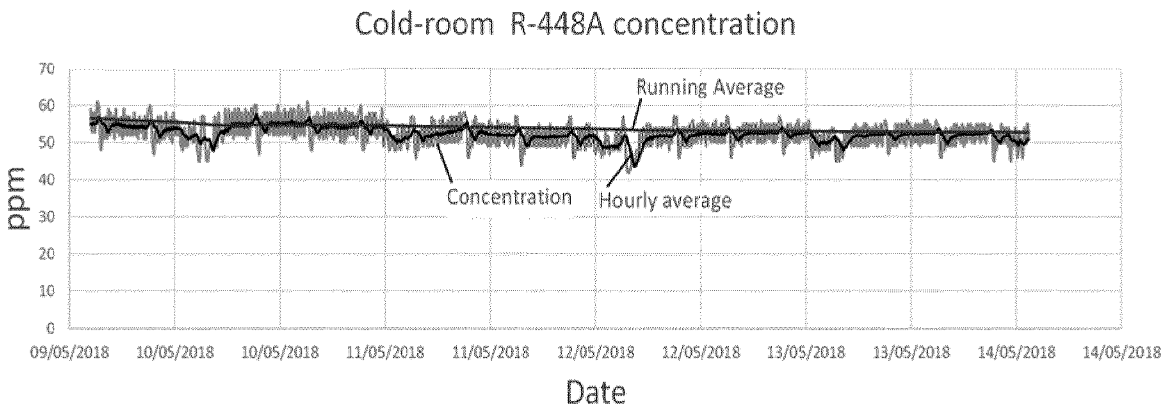
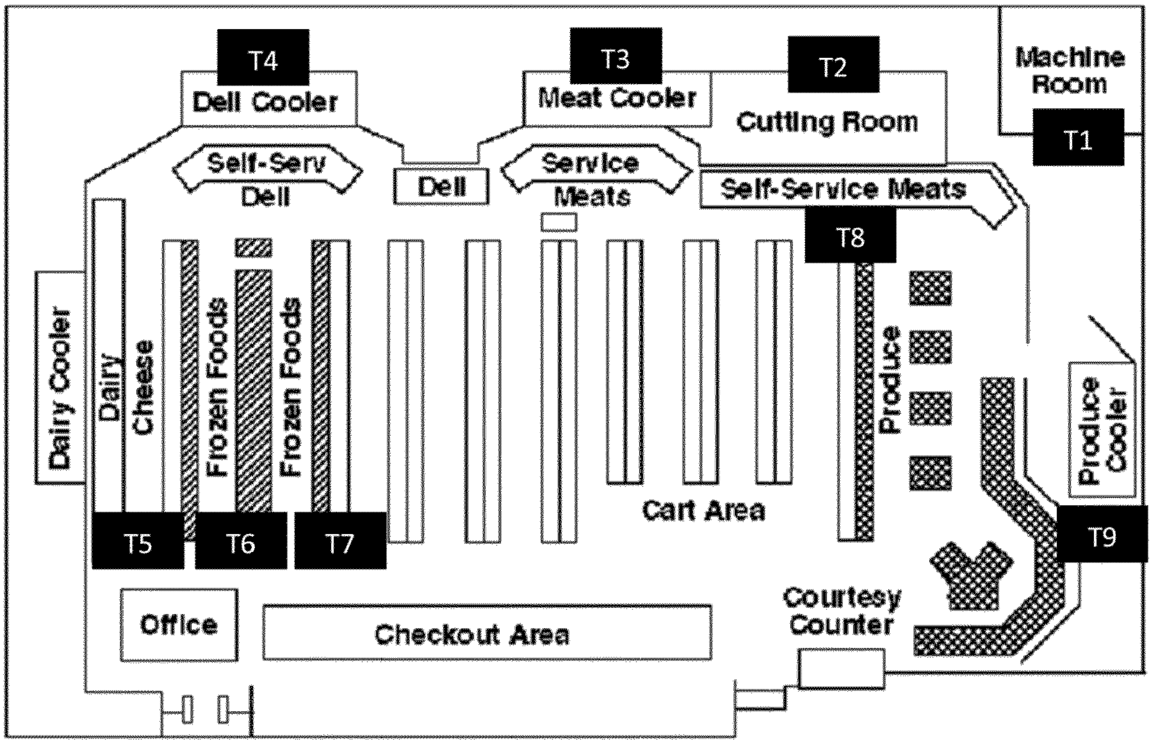


Figure 2



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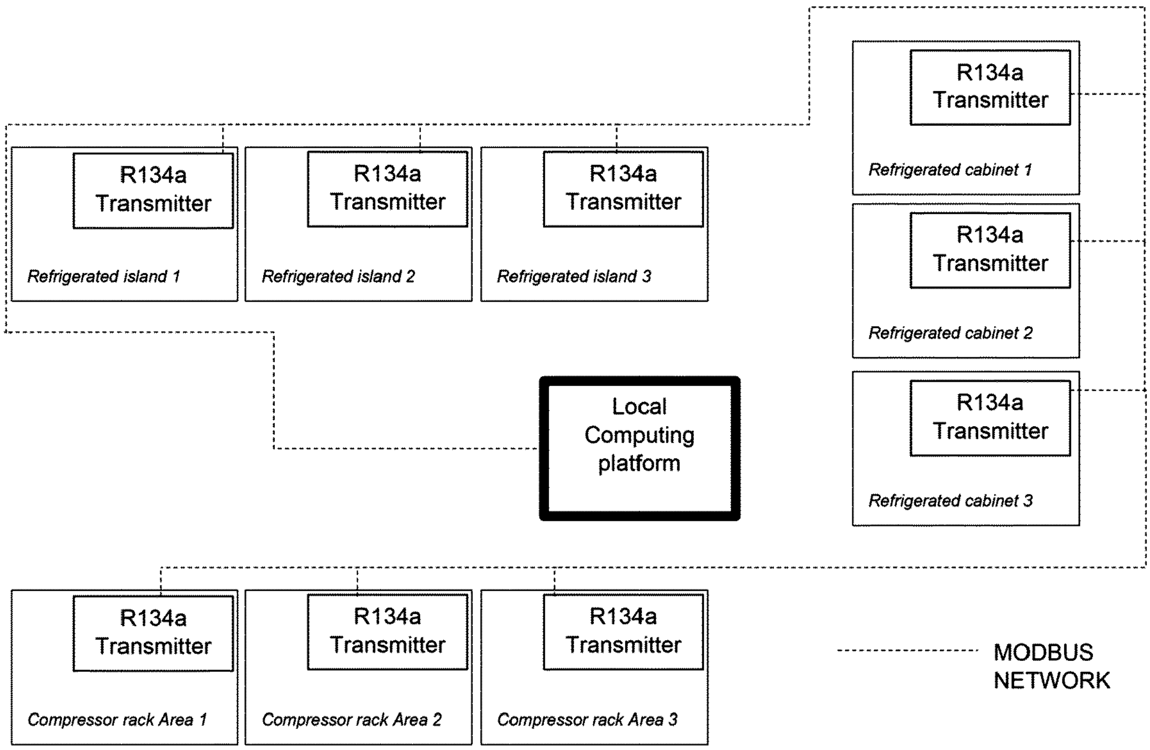

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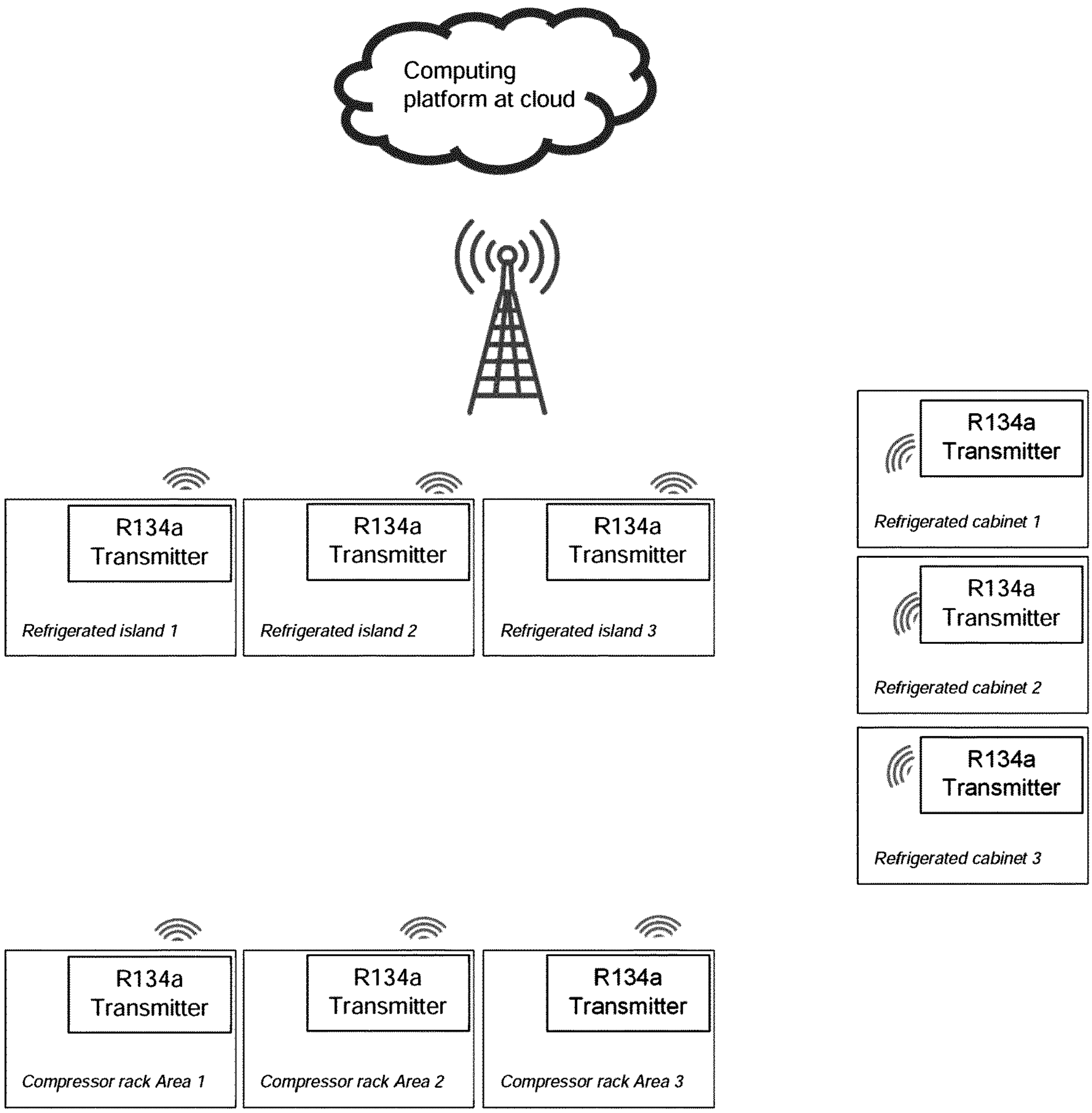

Computing
platform at cloud
R134a
Transmitter
Refrigerated cabinet 1
R134a
Transmitter
Refrigerated cabinet 2
R134a
Transmitter
Refrigerated cabinet 3
R134a
Transmitter
Refrigerated island 1
R134a
Transmitter
Refrigerated island 2
R134a
Transmitter
Refrigerated island 3
R134a
Transmitter
Compressor rack Area 1
R134a
Transmitter
Compressor rack Area 2
R134a
Transmitter
Compressor rack Area 3

Figure 5

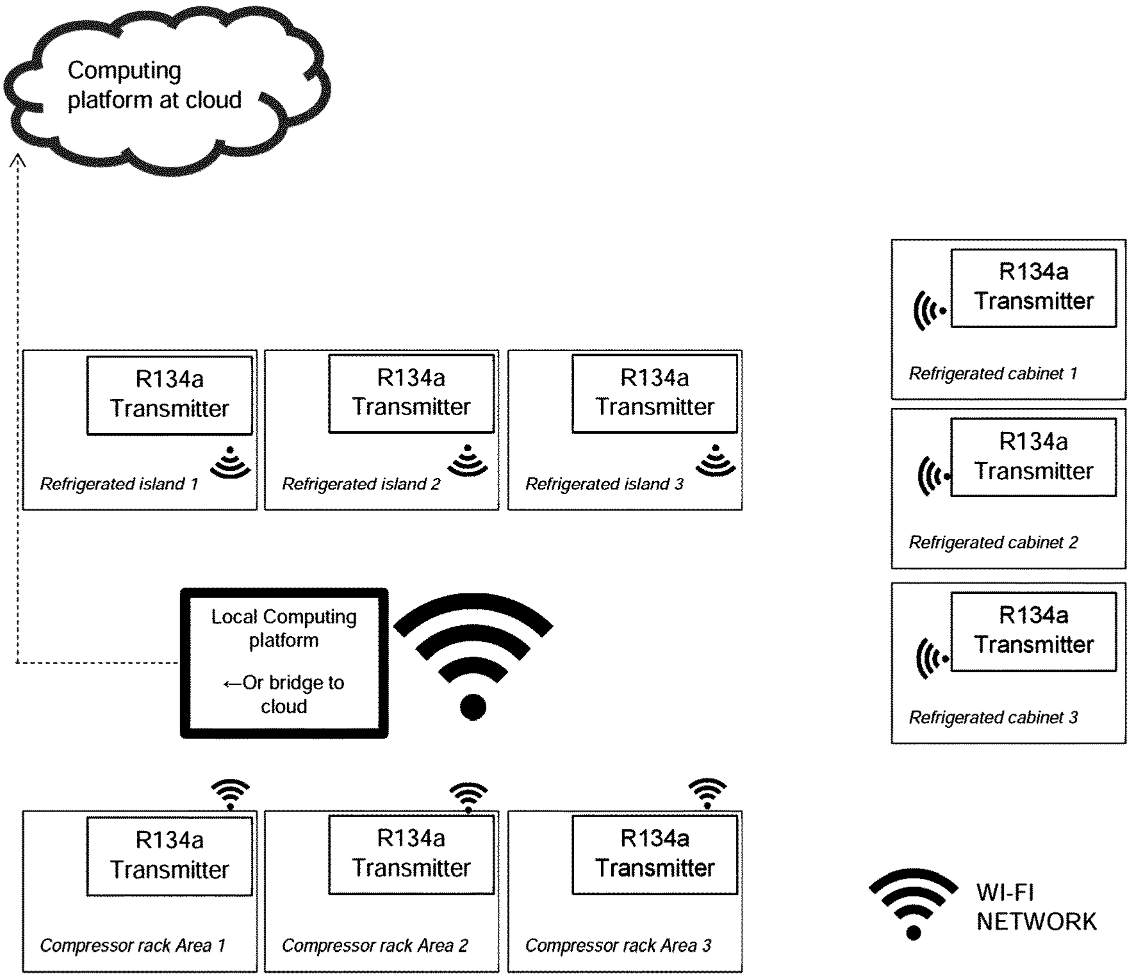

Computing platform at cloud
R134a Transmitter
Refrigerated island 1
R134a Transmitter
Refrigerated island 2
R134a Transmitter
Refrigerated island 3
R134a Transmitter
Refrigerated cabinet 1
R134a Transmitter
Refrigerated cabinet 2
R134a Transmitter
Refrigerated cabinet 3
Local Computing platform
←Or bridge to cloud
R134a Transmitter
Compressor rack Area 1
R134a Transmitter
Compressor rack Area 2
R134a Transmitter
Compressor rack Area 3
WI-FI NETWORK

Figure 6

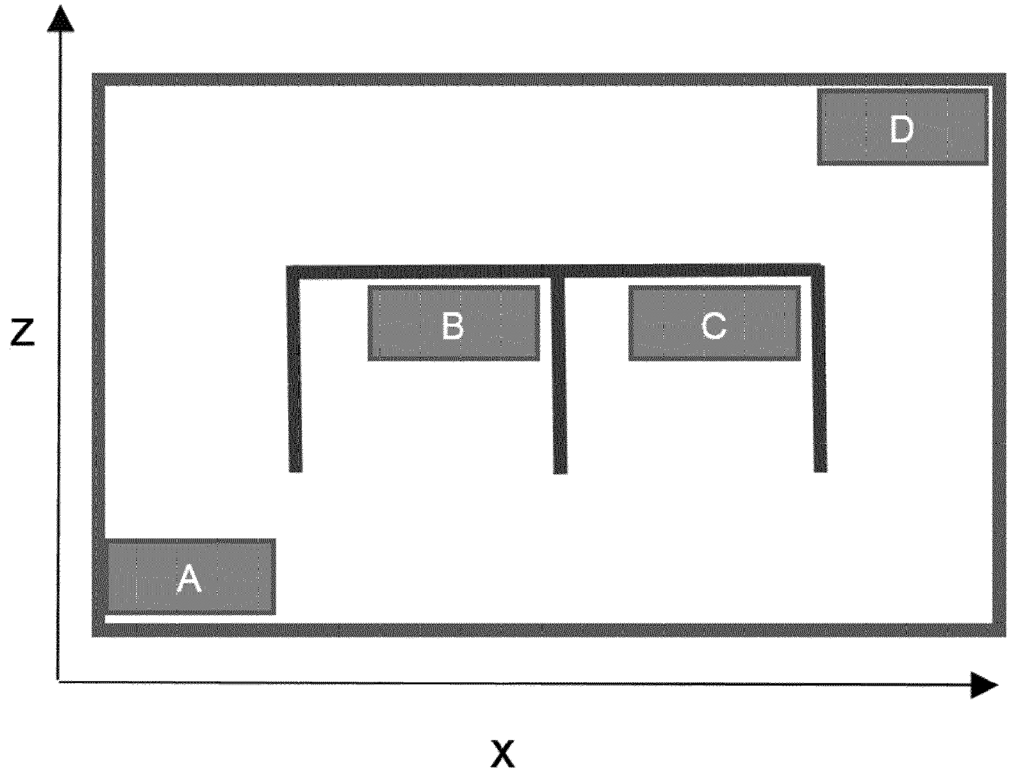


Figure 7

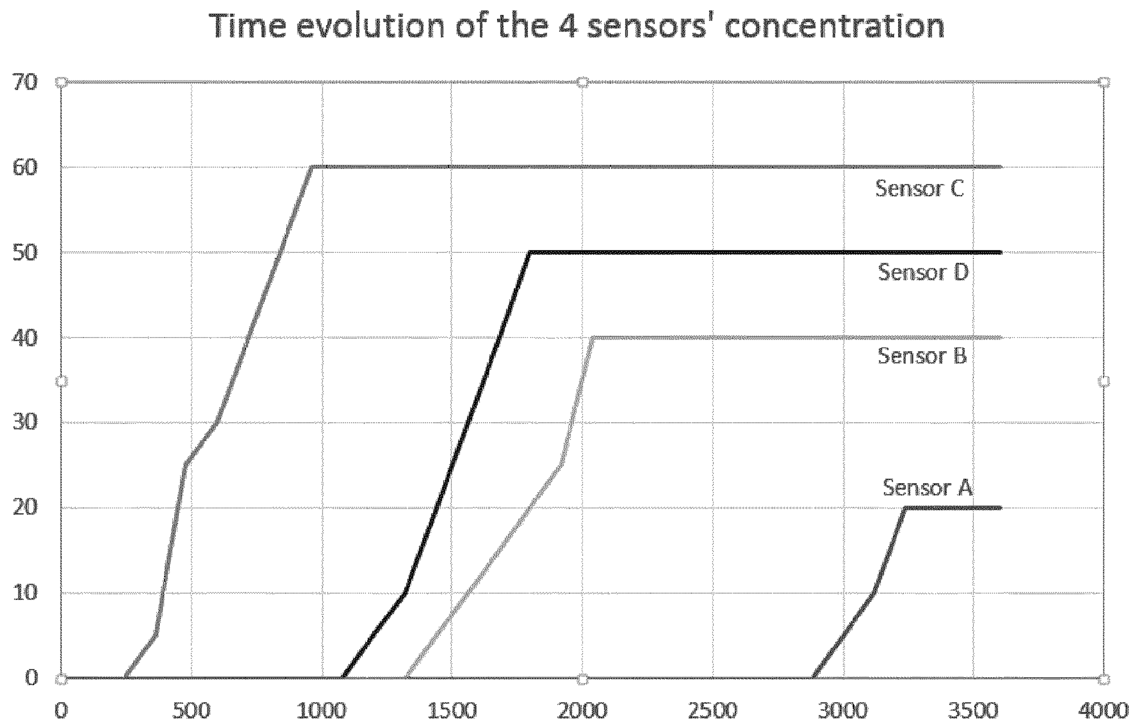
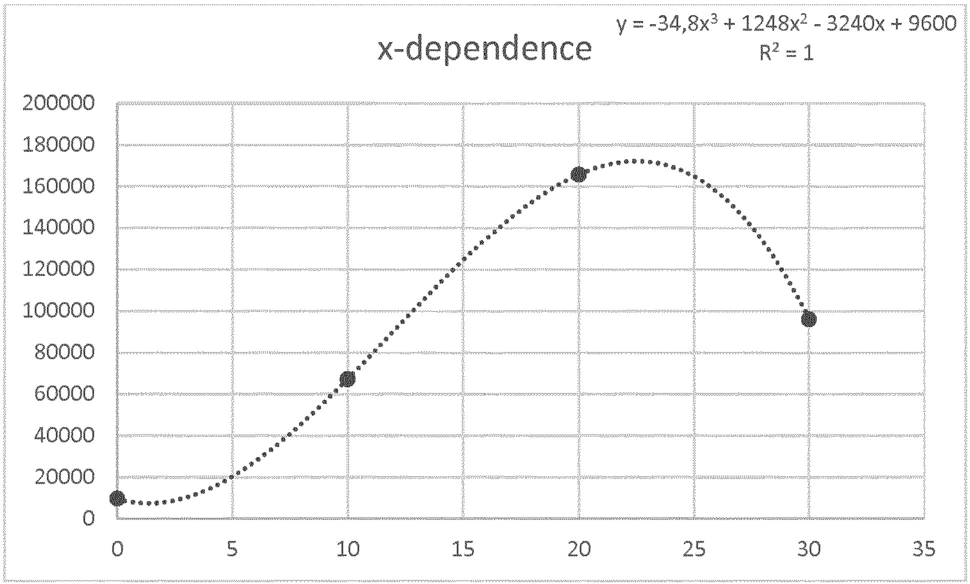


Figure 8



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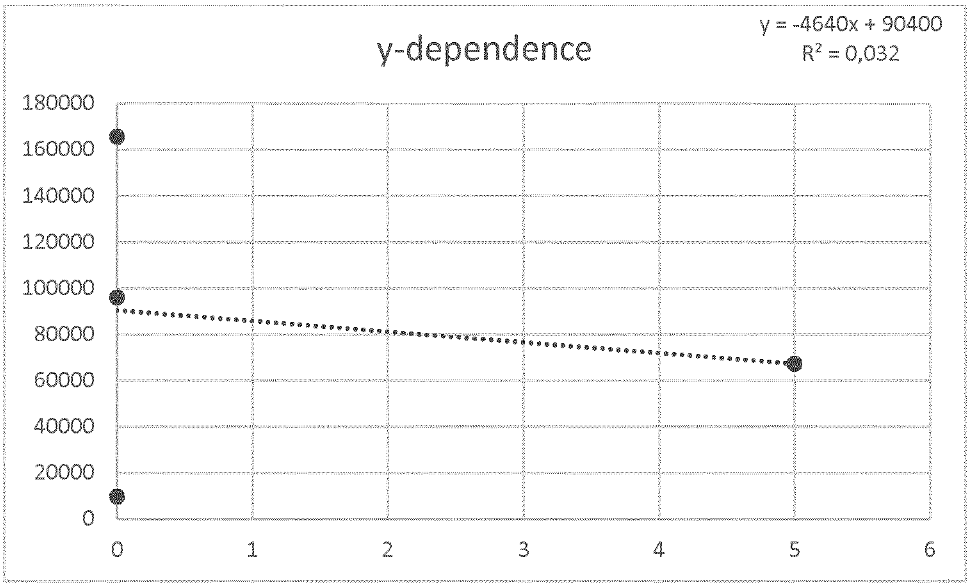

Figure 10

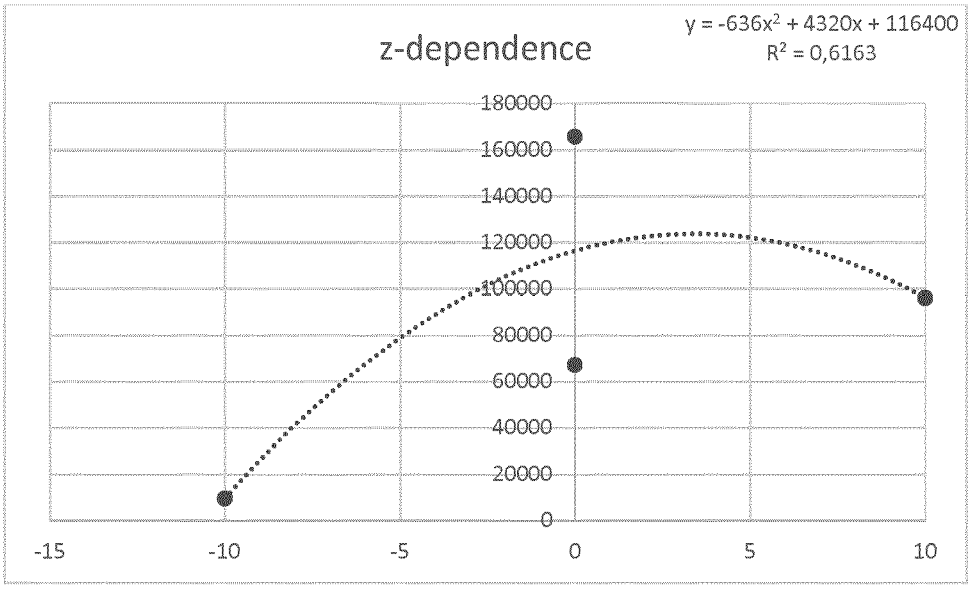

Figure 11

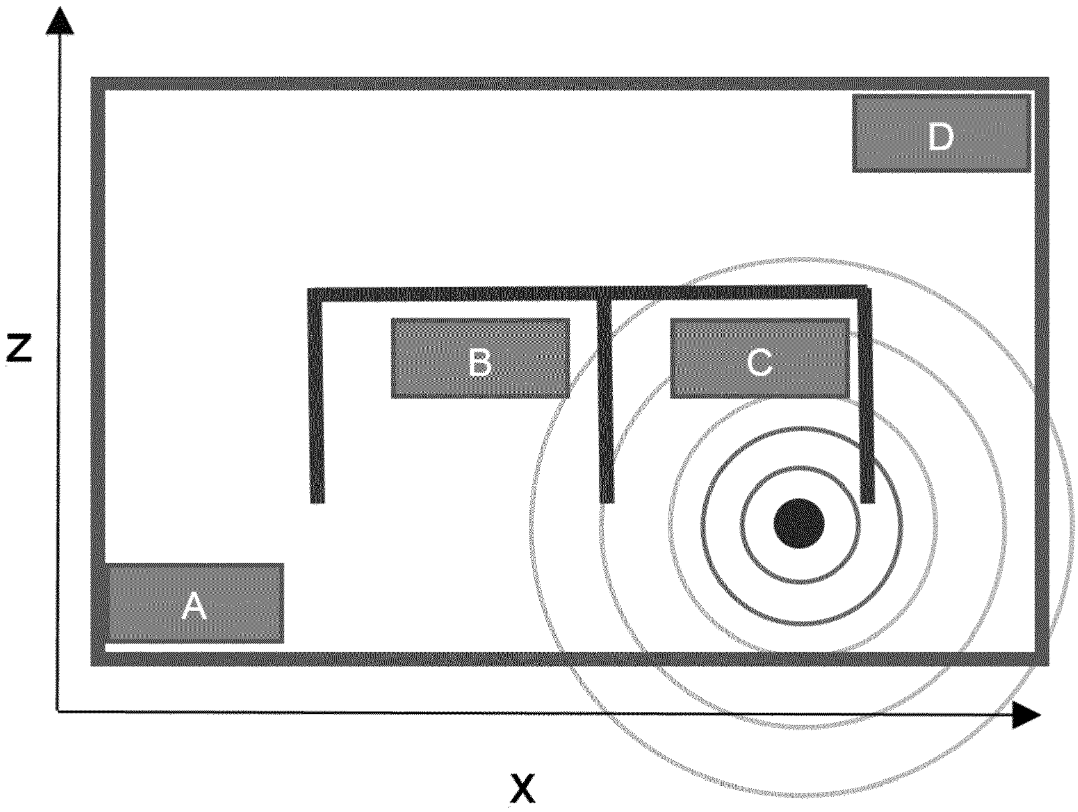

Figure 12

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EUROPEAN SEARCH REPORT

Application Number
EP 19 38 2489

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
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X	US 2011/112814 A1 (CLARK E TODD [US]) 12 May 2011 (2011-05-12) * paragraph [0046] - paragraph [0069]; claims 1, 11 * -----	1-15	
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A	US 2018/187917 A1 (SUZUKI YASUHIRO [JP] ET AL) 5 July 2018 (2018-07-05) * paragraph [0021] - paragraph [0079] * -----	1-15	

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F24F
F25B

The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
Munich	12 December 2019	Silex, Anna

CATEGORY OF CITED DOCUMENTS

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12-12-2019

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