Benefits of Detailed CFD Ventilation Analysis During Early Design Phases

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Most significant hazards faced by offshore platforms, FPSOs, FLNGs, and petrochemical facilities are related to the unintentional release of dangerous material, either flammable or toxic. Natural ventilation can act as a passive safety measure by helping to dilute and disperse released gases. It is a key parameter to assess and improve when possible. The study of its variations is valuable when evaluating a design as it highlights weaknesses and gives insights on possible solutions and optimisations, hence the importance of performing such analysis during early design phases. Unfortunately, most of today's ventilation work focus primarily on meeting specific criteria. For instance, the NORSOK standard requires that any considered area shall have a ventilation greater than 12 Air Changes per Hour (AC/h) at least 95% of the time. However, this only covers a rather limited range of the ventilation conditions at the facility, which is not adequate for assessing and comparing layouts. It should rather require pondering the whole trend to get a full grasp of the ventilation level of the facility.

The use of Computational Fluid Dynamics (CFD) is determinant for ventilation analysis. It allows diving into the details in a rather illustrative way giving a better understanding of the flow field. CFD simulations illustrate and help quantifying the weaknesses of layouts. Thanks to high computing capacities and more accurate CFD models, detailed CFD ventilation analysis can now provide relatively fast and inexpensive insights into potential safety-oriented optimizations during early stages of facility design. Efficiency is key in this new market.

This paper will present guidance on some of the requirements for and benefits of detailed CFD ventilation studies. The paper will use specific examples to demonstrate the value of such studies.

Keywords: *CFD, FLACS, Ventilation, QRA, NORSOK, Risk, Safety, Exceedance curves, FEED*

Introduction

Quite often, during a project execution that would require modifications and/or construction of new installations, several concepts and layouts are considered. The selection can easily become a fairly complex process and would require the definition of decision criteria with associated indicators, the risk level being one of them. However, it is common that parameters that drive the risk picture, such as leak frequencies, process data… still remain unknown or rather coarse at the time of the concept selection. Evaluating ventilation levels in key areas of the installation can reveal valuable information out of the given layouts.

Natural ventilation can act as a passive safety measure through the dilution of unintentional release of dangerous material. Enhanced natural or mechanical ventilation would in most of the cases lower the range of ignitable gas clouds and have a relative positive impact on the final risk. However, ventilation studies are often only considered as a simple task associated to few CFD simulations in QRAs or other risk analysis. This is unfortunate as this task could give valuable insights on the final risk early in the design phase, hence the value of spending more time and efforts on it.

When looking and comparing different layouts, CFD simulations can help providing valuable inputs, helping selecting the layout that would give the best ventilation level. Through the use of methods, stagnant areas, weaknesses , strength and ways of improvement can easily be identified. With today's computer capacities, it is now simple and fast to generate a 3D mapping of the risk. Changes in terms of rotation of the installation or rearrangement of the modules and equipment are quick to evaluate, making the decision process simpler.

Actual methods focus more on achieving ventilation criteria rather than putting extra time and efforts on evaluating optimisation that would enhance the ventilation and lower the risk.

The first section focuses on actual knowledge and requirements with regards to ventilation analysis, frequency wise. The second section describes some tools and methods that would help extracting valuable information from ventilation simulations.

Background and Current Situation

This new perspective was initiated through a project that required performing a ventilation analysis and extracting as many recommendations as possible. The first task was to set up the evaluation criteria, bringing the project team to question the signification and origin of the 12 AC/h criteria. This value is a widely-used criterion imposed by standards like NORSOK that relies on scientific considerations. But is it still relevant for the new technologies and actual layouts? There is an obvious need to set thresholds, to state what is acceptable, but sometimes, does not it bias the consultants' objective making them missing the real point of it? Such as giving insights on how to enhance the situation rather than fulfil a requirement?

Air Changes per Hour (AC/h)

The Air Changes per Hour, also noted AC/h, is a measure that represents the ventilation level of a given area. It has no units. It describes how many times the volume of air is replaced in an hour. It is calculated by determining the difference between the added and removed volumes of air, divided by the volume of the area of interest. But air flow is often not uniform through the area of interest due to the presence of small and large equipment, and the actual air renewal ratio highly relies on the airflow efficiency of the area.

$$AC/h = \frac{60 * Q}{Vol}$$

AC/h: Number of Air Changes per hour
Q: Volumetric flow rate of air (m^3/min)
Vol: Volume of the area L x W x H (m^3).

The AC/h is extensively used as a rule of thumb in ventilation design for enclosed rooms as part of air quality assessment, principally related to mechanical ventilation. NFPA 45 and OSHA regulations on air quality provide minimum thresholds of AC/h to be applied in various areas (Hospital, Chemical laboratories, Schools…). For instance, NFPA 45 requires a minimum of 8 AC/h in occupied laboratories. OSHA regulations states that the ventilation level should not rely on for protection from toxic substances released in the laboratory but ensure the air is continually replaced, preventing increase of toxic concentrations during the working day. A rate situated between 4-12 AC/h would be sufficient. Nonetheless, industrial standards such as NORSOK S-001 extend the use of these recommendations to open areas of Oil & Gas installations, offshore and onshore, and rely on this gauge to assess the ventilation levels. These norms set the minimum thresholds of Air Changes per Hour to be measured over the process areas.

NORSOK Standard S-001

The NORSOK standards are developed by the Norwegian petroleum industry to *"ensure adequate safety, value adding and cost effectiveness for petroleum industry developments and operations. Furthermore, NORSOK standards are, as far as possible, intended to replace oil company specifications and serve as references in the authorities' regulations." [1].*

The NORSOK standard S-001 defines the "*principles and requirements for the development of the safety design of offshore installations for production of oil and gas*" *[1]*. It gives the required standard for implementation of technologies and emergency preparedness to establish and maintain an adequate level of safety for personnel, environment and material assets.

Along the standard, the term "shall" is "*used to indicate requirements strictly to be followed in order to conform to this NORSOK standard and from which no deviation is permitted, unless accepted by all involved parties." [1]*.

Section 16.4.1 of the standard deals with Natural ventilation in hazardous areas and states that *"Natural ventilation in hazardous areas shall be as good as possible and shall as a minimum provide an average ventilation rate of 12 AC/h for 95 % of the time. The ventilation rate shall be provided throughout the area to avoid stagnant zones. […] Natural ventilation shall be documented by calculations and/or model testing. Potential stagnant zones shall be evaluated and precautions taken where considered necessary. […] Location and sizes for ventilation louvers shall be optimised to give required minimum ventilation air change rates for dilution of gases but shall in addition comply with safety risk analysis (gas dispersion, explosion loads etc.) and maintain acceptable working environment/weather protection for personnel." [1]*.

The 12 AC/h value, together with the likelihood of 95%, are common criteria used when evaluating ventilation rates of hazardous areas. The NORSOK standard S-001 presents the 12AC/h value as a requirement to be met but does not give more details about the logic behind it. However, this paragraph refers to NORSOK Standard H-001.

NORSOK Standard H-001

The NORSOK standard H-001 gives the principles and requirements for the heating, ventilation and air-conditioning systems on offshore production installations. It served as the base document for the international development of ISO 15138 "Petroleum and natural gas industries – Offshore production installations – Heating, ventilation and air-conditioning", published in November 2000.

The section 5.3.1 of the document deals with natural ventilation and states that "*Natural ventilation in hazardous module areas is from a safety point of view considered sufficient when an average ventilation rate of 12 AC/h in areas is met for 95 % of the year. Potential stagnant zones shall be evaluated and precautions taken where considered necessary from safety risk analysis. […] If required by project specific risk analysis or to optimise working environment conditions, adequate ventilation requirements in a hazardous area can be calculated for dilution of estimated fugitive emissions. […] The quantity of air can be calculated from data in API 4589 using the methodology given in API RP 505." [2].*

The NORSOK standard H-001 differs from NORSOK standard S-001 by informing that this requirement relies on a safety point view and considers that this value is sufficient. It also mentions the methodology developed in API Recommended Practice 505 and data from API 4589.

API RP 505 and API 4589

The appendix B of API RP 505 details the method for the calculation of the minimum air introduction rate necessary to achieve what is defined as adequate ventilation, based on the evaluation of fugitive emissions. The objective is: based on the hydrocarbon leakage rate anticipated under normal operations, "*sufficient dilution air must be added to the space in question to ensure that the concentration of flammable vapor or gas is maintained below 25 percent of the Lower Flammable Limit (LFL) for all but periods of process upset, abnormal equipment operation, rupture, or breakdown."* [3]. The method described in the document is adapted from *Module Ventilation Rates Quantified*, Oil and Gas Journal, W.E. Gale, December 23, 1985, p41.

Data and methods from API 4589 help determining the anticipated fugitive hydrocarbon emissions. The total anticipated fugitive hydrocarbon emission is obtained by combining the number of relevant hydrocarbon handling components with their anticipated hydrocarbon fugitive emission factors detailed in tables of API 4589. The total anticipated gas service emission mass rate is then converted in volume rate through the Gas and Charle's Gas laws. The minimum ventilation rate to keep a concentration corresponding to 25% of the LFL is finally calculated using the formula given below. There is a safety factor of 4 applied to the final result in the described method.

$$Q = 4 * \frac{E * V}{60 * M * C}$$

Q: Volumetric flow rate of air (m^3/min)
E: Fugitive hydrocarbon emission rate (kg/hour)
V: Molar volume (m^3/kg mole) at the given temperature
M: Average molecular weight
C: Concentration of hydrocarbon in air (%)

Example:

Considering a total of 9500 components (Connections, valves, open ends, others) for an Offshore Oil & Gas facility, the fugitive hydrocarbon emission rate reaches the value of 1 kg/hour. We then consider in this example a material with an average molecular weight of 19.5, an LFL of 0.05 %, and a molar volume of 24.9 m^3/kg mole. It gives a volumetric flow rate of air of 6.8 m^3/min.

$$Q = 4 * \frac{1 * 24.9}{60 * 19.5 * 0.25 * 0.05}$$

For an 8000 m^3 offshore module, it then requires a minimum AC/h of 0.05 to keep the concentration of hydrocarbons below 25% LFL.

If we consider 9500 components, but now in an Onshore Gas Production facility, the fugitive hydrocarbon emission rate goes up to 4.2 kg/hour. The volumetric flow rate of air is then 28.6 m^3/min, and the required minimum AC/h is 0.21.

In this example, there is a factor of 240 for the offshore facility, and 57 for the onshore facility compare to the 12 AC/h value required by the standard, and that is including the safety factor of 4. It quantifies the large gap existing between what is needed and what is required. The number of equipment could be multiplied by 100, and the necessary AC/h would still remain below the requirement. This quick exercise also illustrates the high dependency of the AC/h calculations on the number of components and considered volume. The latter having the most impact and being user dependent.

The tables from API 4589 are based on an extensive survey performed in the 90s on Gulf of Mexico facilities. Technologies have improved since and the type of facilities has evolved. FPSO and FLNG layouts are quite different than offshore layouts from the 90s and do not always consider distinctive fire zones. For instance, cargo decks would include a large number of handling hydrocarbon equipment over a large volume. The measured AC/h would then be considerably low, whereas it does not necessarily mean it is under ventilated, questioning the use of the criteria for such areas.

Interpretation of the Criteria

Based on the few calculations detailed above, it seems that the criteria of *"12 AC/h 95% of the time"* defined in the NORSOK standards is a fairly conservative requirement. It is not wrong to target such high value to be on the safe side, but it might somehow bias the real value of ventilation analysis. As stated in the first part of NORSOK S-001, the ventilation level shall be as good as possible. By specifying a target value, consultants are more likely to focus on meeting this value without looking at the meaning and real potential of ventilation analysis. There is a necessity to approach the ventilation studies with another angle than just satisfying AC/h thresholds. It is valuable to investigate on how to reach a better ventilation level for the layout. This is especially relevant in the early design phases of a project as the ventilation analysis are easy and quick to be performed and would give valuable information on the final trend of the risk, highlighting weaknesses and helping guiding the choice of layout.

The AC/h concept seems, as values, more suitable to air quality assessment than for the dilution of fugitive hydrocarbon emissions under normal conditions. The AC/h value of 12 is thus logically related to air quality requirement. However, AC/h trends can be of interest when comparing layouts and options. It would quantify how good a layout or option could be in terms of ventilation levels.

Benefits of Ventilation Analysis in Early Design Phases

With today's computer capabilities, ventilation simulations are easy to setup and quick to run. As described in the following sections, ventilation analysis can give valuable information with regards to the risk level, weaknesses and bring to light solutions. Any rerun of an altered layout would be quick and the understanding of the effects immediate. Hence the benefit of performing ventilation analysis early in the design phase.

Two ways to evaluate ventilation simulations are presented in this paper. The first one is based on the use of the CFD tool FLACS and its post-processing software FLOWVIS. It relies on visualizing the ventilation levels in details in a 3D model. It is the state of the art in terms of risk visualization. The second way lies on tabulated AC/h that would give the trend of the ventilation pattern and help comparing and determining the best layout.

The purpose of the following sections is not to analyse particular cases but rather present methods and tools to develop the potential of ventilation analysis.

Visualisation

The use of 3D CFD codes such as FLACS allows 3D visualisation and guarantees a good understanding and interpretation of the scenarios. Through rotation, filtering, change in scale, transparency, it is possible to dig into every little detail of the flow field and highlight weaknesses of the layout and high risk areas, such as stagnant areas. Today's computer capacities allow to run a larger number of simulations, faster and with increased accuracy. New tools in FLACS allow combining simulation results in a smart way, enhancing the understanding and highlighting interesting features, especially when combined with weather statistics.

In figure 1 below, 3 plots extracted from the FLACS post-processor FLOWVIS represent 3 ways to investigate on the ventilation patterns. The top one illustrates the flow speed for a given wind speed and direction. The middle plot corresponds to the flow speed over the installation for an aggregation of all wind directions for a given wind speed, in this case 2 m/s, regardless of their probability of occurrence. The bottom plot represents the mapping of the probability of having at least 1 m/s. This plot accounts for all wind directions and speeds, including their probability of occurrence. The dark blue colour highlights the areas that have a probability of having at least 1 m/s located between 10% and 20% of the time. What is not coloured has a probability below 10%.

The plot on the top is the most common way to go through CFD simulations. It requires going through each simulation one by one in order to identify specific areas, such as stagnant areas due to equipment or congestion, and regroup similar ventilation patterns together. It helps visualizing the impact of equipment on local ventilations, and units on a larger scale for given conditions. In this case, the illustration shows that the wind from the south-east direction does not easily go through the congested areas, except in the vicinity of large gaps located in between units. However, this task can be time consuming and it may not be very efficient when you want to have a clear overview on a more global scale.

The middle plot gives another perspective on the global ventilation level. The aggregation of all wind directions highlights the stagnant areas that will benefit the low, but most frequent, leak rates. As a result, depending on the dangerousness of the area, solutions can either be in terms of layout, or in terms of process modification to avoid any significant cloud development and/or ignition sources around these areas. In this plot, the gaps between the units clearly stand out with their high flow velocity defined by the dark red colour. On a larger scale, there is not any particular module that benefits or suffer from any equipment or unit. The blue colour, accounting for wind speeds between 1 and 2 m/s, located in the middle of each module would require a more thorough investigation to assess the local ventilation. However, this 3D mapping does not account for the weather statistics. That could imply that well-ventilated areas presented in this plot could be in reality poorly ventilated due to some low probability for the wind direction favouring this unit.

This is the reason why there is a need to look at the risk picture and combine the CFD results with weather data, such as in the bottom plot. This combination corresponds to a more realistic and accurate picture of the ventilation potential. The way it is presented in this plot is the likelihood of having more than 1 m/s. Whatever is not coloured means that flow speed will be above 1 m/s not more than 10% of the time. In the presented case, the prevailing wind is from the south-east direction. That explains why the units located on the north-west corner of the facility do not seem to benefit from wind over 1 m/s. As a result, it highlights that sensitive units in the north-west corner may experience high risk with regards to the presence of flammable or toxic cloud due to low dilution level. The risk can be quantify by quantifying the 3D mapping with leak frequencies and inventory size distribution.

The flexibility of the tools makes it easy to investigate a simple rotation of the facility by reattributing the frequencies to the different directions. That way, the weight of the different speeds and directions is redistributed and would give another insight on what can be changed to improve the global and local ventilation levels. 3D representations are illustrative and easy ways to illustrate and understand the phenomenon. However, when dealing with two different flow patterns, it can become difficult to apprehend which layout is the best in which situation. That is where numerical comparison can help.

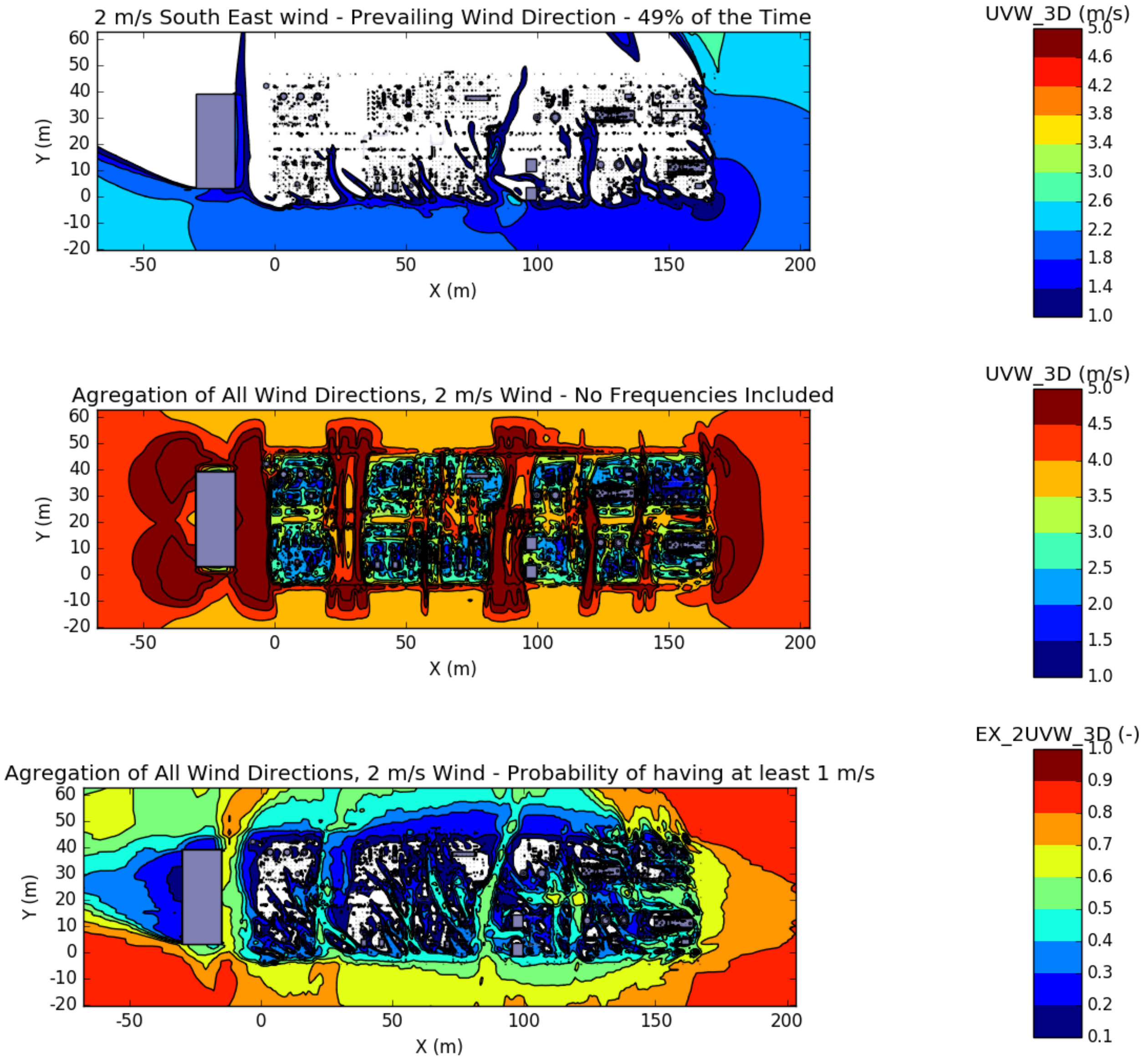


Figure 1 - Different ways of visualizing CFD ventilation results.

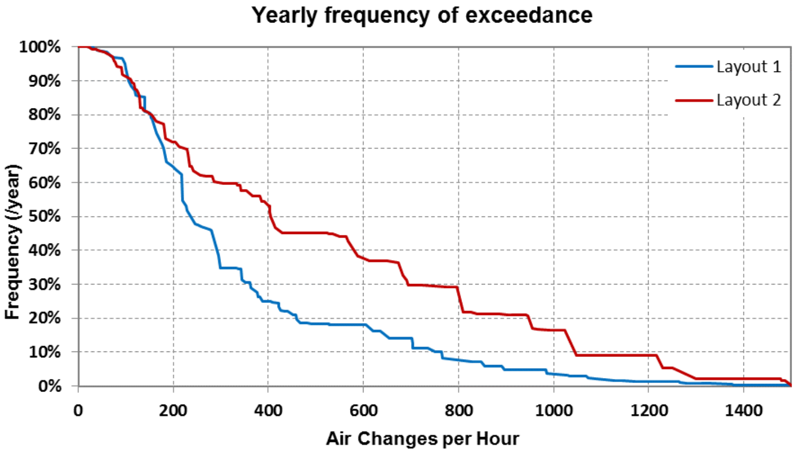
Numerical Comparison: Exceedance

The idea behind ventilation analysis is not only to assess in details the ventilation level of a given layout, but also investigate the opportunity of improving it, through a change of layout for instance. It can vary from a simple rotation of the whole installation to a complete rearrangement of the units. Different layouts would give different ventilation conditions that need to be evaluated and compared.

Tabulated AC/h values extracted from the CFD simulations for the different areas can be used. When combined with the weather data, they can be presented through different ways as presented in figure 2 below.

The most common way remains the exceedance curve as presented in the top part of figure 2. Plotting exceedance curves for different layouts is an easy task to compare trends. The exceedance plot is a good example of limitations of the "12 AC/h 95% of the time" requirement described in section 1. When looking at the 95th percentile in the top chart of figure 2, Layout 1 has an AC/h larger than 12, but also slightly larger than for Layout 2. However, it is clear when looking at the global trend that Layout 2 has a better overall ventilation level.

Layouts can also be compared one against the other, such as in the plots located on the bottom of figure 2. In this case, the orange and red lines limit the area when the values diverge by more than 20% and 50% respectively. The added value is the quantification of the discrepancies between the layouts compare to the exceedance curves.



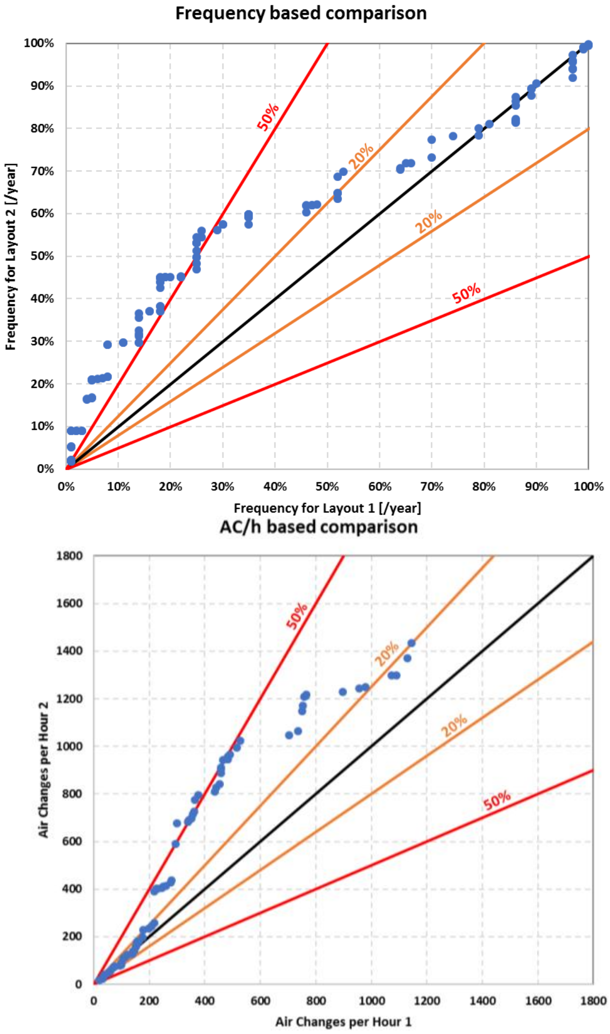


Figure 2 - 3 different ways to present numerical ventilation comparison results

Numerical Comparison: Root-Mean-Square Deviation (RMSD)

Trends presented in the previous section can give you most of the essential information, but in some situation, it can be helpful to go down to one value. It has its limitations as one value does not represent the whole trend, like the 95th percentile rquirement, but can be in some way representative to the global ventilation level.

Numerous methods from various industry were developed to differentiate functions, curves, signals or shapes. It is a common and often difficult problem in analytical chemistry, physics, spectroscopy, economics, biology or medical domains. Such methods are for instance used to monitor and quantify the effects of new medication or molecules and assess the degree of their efficiency. Shape comparison is used in photography to superimpose shapes when post-processing pictures. The human eye remains the best tool for shape comparison, but when it comes to comparing several curves with various shapes, and rank them, numerical solutions become necessary. The used approaches can range from simple RMSD comparison to very sophisticated methods. With regards to ventilation analysis, the level of details is that simple methods such as RMSD would be sufficient.

The RMSD method is commonly used in experimental work to measure the difference between predicted values and the ones actually observed. It is a good measure of accuracy but only to compare differences between layouts for a given variable and not between variables. Normalizing the RMSD facilitates the comparison between datasets such as AC/h or frequency based comparisons. Lower values indicate less residual variance. The closer to 0 the NRMSD is, the more likely the curves are.

$$NRMSD = \frac{\sqrt{\frac{\sum_{t=1}^{n}(x_{1,t} - x_{2,t})^2}{n}}}{x_{1,max} - x_{1,min}}$$

NRMSD:	Normalised Root-Mean-Square Deviation
$x_{1,t}$	Data points
n:	Number of data points

The value of this method is to summarize the similarities with one value. In contrast with the NORSOK requirement of 12 AC/h 95% of the time, the Normalised Root-Mean-Square Deviation accounts for the whole range of values and not only one portion of the exceedance curve. However, a lot of information and variations are lost in the calculations, and it remains important to relate this value to the exceedance curves to get the full picture. It is a complimentary method to the ones presented in the first sections.

Conclusion

The relevancy of the criteria set for ventilation levels by the standards has been questioned. It seems that the requirement of having 12 AC/h at least 95% of the time is more driven by air quality requirements than safety purposes as illustrated in the example. It is not wrong to voluntarily require such high level, but setting up a target value may be counterproductive as it bias the real purpose of the study. Many conclusions of ventilation studies only look at the 95th percentile AC/h value to the criteria but do not assess and highlight the weaknesses and ways of improvements when necessary.

Moreover, based on the scientific considerations behind the requirement, it does not seem that the AC/h indicator is the most adapted indicator for assessing the ventilation level. As detailed in the first section, the AC/h requirement calculation is highly dependent on the number of components and more importantly on the volume of the area of interest. As a result, large volumes, such as cargo decks for FLNGs, would be depicted as poorly ventilated areas, even though there is a sufficient flow. AC/h is a simple indicator of the ventilation level whose levels can be questionable but trends to be used for comparison.

Different ways of illustrating the flow in the facilities can be of interest when evaluating the risk level of a facility, especially in the early design phase. As presented, 3D representations of flow speed and weather data, together with leak frequencies and inventory characteristics, helps highlighting the weaknesses, stagnant areas, and give insights on what can be done to maximize its potential. Other tools such as exceedance curves and NRMSD method allow comparing layouts and thus help making a decision.

With such available tools and methods, it is now easier to draw early conclusions on risk trend with ventilation analysis but also bring attention on some key points of the layout. With actual computer capabilities, ventilation CFD simulations are easy to setup and quick to run and allow a fast feedback when comparing layout or looking for improvement, hence the important on performing such studies during the early design phase.

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