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# Analyzing the dispersion of cargo vapors around a ship's superstructure by means of wind tunnel experiments

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## 1 Introduction

Chemical tankers are confronted with regular tank cleaning as a result of the large number of tanks and the wide variety of products they carry. While cleaning and venting cargo vapors into the atmosphere, our measurements as described in W. Jacobs et al.(2010) have shown that during these operations the concentrations near the ship's accommodation can be relatively high. Especially when dealing with toxic cargoes these cargo vapors might endanger the crew's health during specific operations. Examples of such operations are loading, cleaning, gas-freeing or ventilating cargo tanks. Often vapor balancing is considered as the solution to reduce vapor emission to zero during loading and discharging operations. However this is only valid for port operations. The drawback of vapor balancing is that during discharge operations the terminal sends cargo vapors back on board in a ship's tank that after discharging has to be cleaned for the next cargo. The only option for the crew is to vent these vapors in the atmosphere once the ship is at sea. The data from the aforementioned publication was obtained after two weeks of on-board measurements on the North Sea and the Baltic Sea. This route seems very interesting since chemicals are transported in large quantities between the different ports in the area. The amount of liquid chemicals in bulk handled annually in the Baltic Sea ports is over 11 million tonnes and about one half of that (roughly estimated 5.0 – 6.3 million tonnes) is

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handled in Finnish ports (Posti and Hakkinen, 2012). The chemicals handled in the largest quantities in the Baltic Sea ports are methanol, sodium hydroxide solution, methyl tert-butyl ether (MTBE), xylenes, pentanes, ammonia, phosphoric acid, sulphuric acid, and ethanol and ethanol solutions (Posti and Hakkinen, 2012). Exact figures are available for only the Finnish ports and are listed in appendix table 3.

The measurements we performed can be classified as time-consuming and expensive. At first we had the intention of investigating more ships but given the aforementioned drawbacks we were obliged to investigate a less time-consuming and cheaper alternative. Another disadvantage of the on board sampling is the fact that we did not have control over all parameters. Relative wind direction, for example, was liable to change during the sampling period because of a change in true wind direction or because of a change in the vessel's course. Especially in relatively narrow and/or high-density traffic areas such as the North Sea or the Baltic Sea these changes in course occur frequently and change the air circulation around the superstructure significantly. In addition, not only the wind direction will change when altering course, but also the relative wind force. On a 14-day cruise such as this not all situations will manifest themselves and this leads to gaps in the measurements, for example relative wind directions where no data were available as they did not happen during the measuring period. In order to overcome this problem and to have more control over the sampling conditions we decided to continue the sampling in a wind tunnel. The aim of this study is to give an overview of cargo vapor concentrations around the ship's accommodation under well-known circumstances based on wind tunnel experiments.

## 2 Methods

For this research we used the wind tunnel of Peutz, at Molenhoek in the Netherlands. This tunnel is a closed low speed wind tunnel with an effective working section of 3m x 3m x 1.8m and an overall length of about 8 m. For the tests we decided to take the same ship as the one described in W.Jacobs et al.(2010) as it has a standard layout which is frequently used on other chemical carriers. Comparing the width of the tunnel with the length of the ship, we decided to choose a model scale of 1/100 in order to keep obstruction of the air stream by the model to a minimum, whilst still keeping the model sufficiently detailed. Prior to any wind tunnel experiment we generated in the tunnel a marine boundary layer to the same scale as the model by means of 5 Counihan spires in combination with a castellated barrier wall. The surface roughness was created by the use of a carpet. The average wind speed was set to $U_{10} = 2.72$ m/s. This relatively low wind speed was chosen in order to simulate the conditions with minimum air mixing leading to the highest concentrations. The so created atmospheric boundary layer can be described by a power law:

$\frac{U(z)}{U_(ref)} = (\frac{z}{z_(ref)})^{\alpha}$

where U(z) is the mean velocity at height z, and $U_{(ref)}$ is the mean velocity at the reference height $z_{(ref)}$. For $\alpha$ a value of 0.11 has been chosen to simulate the sea surface in calm weather (Argyriadis, s.d.). For offshore winds the Danish Energy Agency (The Danish Energy Agency, 2001) recommends the use of the logarithmic law with a roughness length of $z_0 = 0.001$ m. Det Norske Veritas (Det Norske Veritas, 2010) accepts values of $z_0$ between 0.01m and 0.0001 m for a marine boundary layer. The logarithmic law describes the boundary layer as follows :

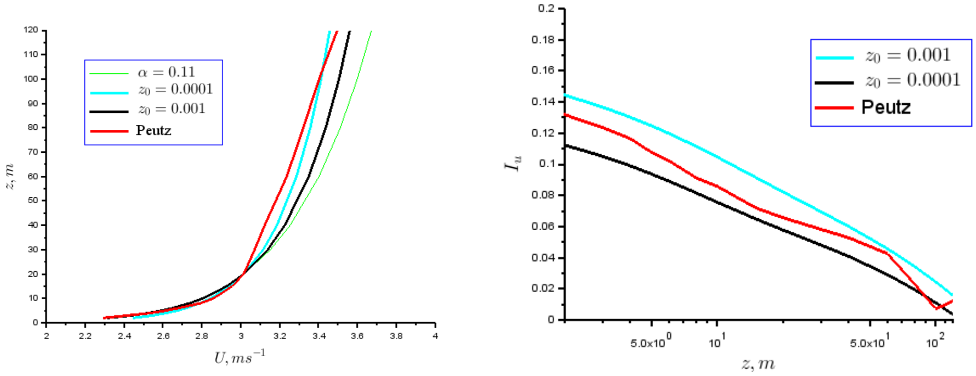
$U(z, 10min) = U(z_r, 10min) * \frac{ln(z/z_0)}{ln(z_r/z_0)}$ with

| | |
|---|---|
| U(z, 10min) | 10 minute averaged wind speed at height z |
| U($z_r$, 10min) | 10 minute averaged wind speed at reference height $z_r$. |
| z | height above still water line |
| $z_r$ | the reference height above still water line (hub height) |
| $z_0$ | roughness length |

Figure 1a shows the power law curve, the logarithmic law curve and the resulting curve in the Peutz wind tunnel. The values of wind speed and turbulence intensity in the wind tunnel have been obtained by means of hot wire anemometry. Some cross-wind profiles were also measured to check the symmetry of the wind speed profiles.

For the longitudinal turbulence intensity we used the formula of ESDU 1985, as cited in the Wind Energy Handbook (Burton, Jenkins, Sharpe, and Bossanyi, 2011). The turbulence intensity depends mostly on the surface roughness. Since we will work in calm conditions only, we tried to simulate a value of $z_0$=0.001 or less. Figure 1b compares the turbulence intensity in our wind tunnel to the turbulence with $z_0$=0.001 and 0.0001 calculated with the formulae :

$I_u = \frac{\sigma_u}{\bar{u}}$ with



(a) boundary layer

(b) turbulence intensity

Figure 1: (a) Comparison of the power law curve with exponent 0.11, the Peutz boundary layer and the logarithmic curves for a roughness coefficient $z_0$ = 0.001 and 0.0001. (b) Comparison of turbulence intensity for a roughness coefficient $z_0$ of 0.001 and 0.0001 with the turbulence intensity in the Peutz wind tunnel

$\sigma_u = \frac{75\eta(0.538+0.09m.(z/z_0))^p u^*}{1+0.156 ln(u^*/fz_0)}$
$\eta = 1 - 6fz/u^*$
$p = \eta^{16}$
$u^*$ being the friction velocity $= U(z) * \kappa/[ln(z/z_0) + \Psi]$
$\kappa$ is the von Karman constant(abt. 0.4)
$\Psi$ is an indication of air stability and shear wind condition
f is the Coriolis parameter $= 2\Omega sin(|\lambda|)$ where $\Omega$ is the angular velocity of the earth's rotation, and $\lambda$ is the latitude.

The aim of these measurements was to determine a concentration coefficient for the various setups. The method used was the release of a tracer gas in combination with photo ionization detectors. The tank outlets were simulated by using small diameter tubes releasing isobutylene. Three different source locations were used during the experiment, namely two manholes as tank outlet and the pressure vacuum (PV)-valves amidships. PV-valves, or high velocity valves, are valves which open at a pre-defined tank pressure and release the tank atmosphere at a minimum velocity, f.e. 30 m/s. It is especially interesting to compare concentrations using a PV-valve as outlet, with concentrations using a manhole as outlet, since the International Maritime

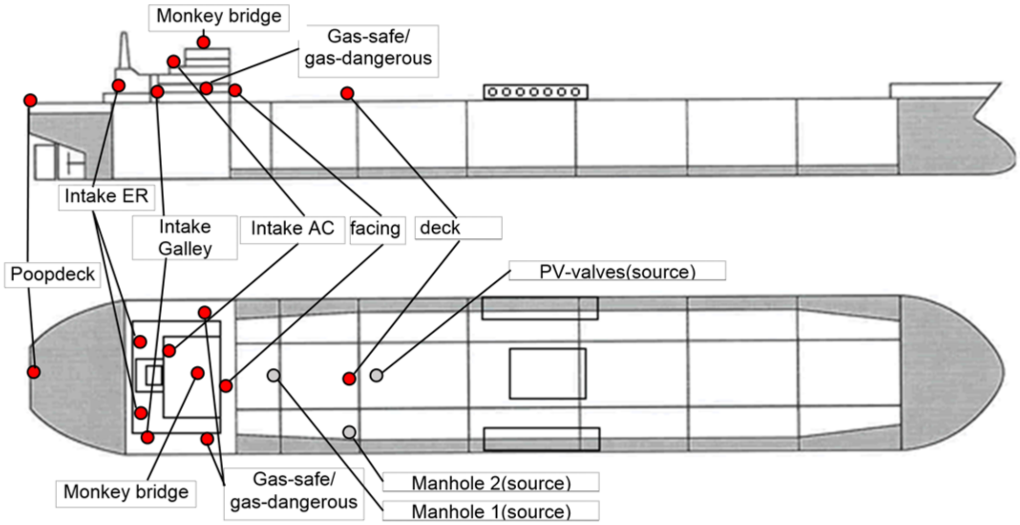


Figure 2: overview of the chosen immission points around the ship's superstructure

Organisation (IMO) clearly states in the IBC code (The International Maritime Organisation, 2007) that venting of cargo vapors can only be done by manholes on condition that the concentration of cargo vapors is below 30% of the lower flammable limit of the product or, in the case of a toxic product, does not present a significant health hazard. If these conditions are not fulfilled, vapors must be evacuated by the PV-valves. On the model eighteen immission points were chosen over and around the superstructure in order to give a detailed overview of the concentration of the tracer gas around the ship's accommodation. An overview of the major sampling points is shown in figure 2. In this figure the expression 'gas-safe/gas-dangerous' stands for the imaginary separation line between the gas-safe or accommodation area aft, and the gas-dangerous or cargo area forward of this line as defined by the international code for the construction and equipment of ships carrying dangerous chemicals in bulk (IBC code).

The dispersion of the tracer gas is indicated by the concentration coefficient

$K = \frac{C.U_{10}.H^2}{Q}$

where C is the measured mean concentration, $U_{10}$ is the upwind free stream velocity at 10 m height and H the scale used in the tunnel. Q is the volumetric flow rate of the tracer gas. In order to compare wind tunnel results with on-board measurements, K-values have to be used in the calculation of immission concentrations C. This is done by using the formula for the immission concentration C :

$C = \frac{K.Q_{source}}{U_{10}+K.\Phi_v}$

where K is the concentration coefficient ($1/m^2$), $Q_{source}$ is the volumetric rate of the tracer gas ($m^3/s$), $U_{10}$ the wind speed (m/s) at 10 m height and $\Phi_v$ is the total outlet flow, namely the sum of Q and the mixed air rate($m^3/s$). In total 6 series of measurements were performed with settings as given in table 1. The increase in wind speed for measurements 5 and 6 was obtained by decreasing the PV-valve outlet velocity.

| measurement number | source | immission points | wind speed $U_{10}$ (m/s) |
|---|---|---|---|
| 1 | manhole 1 | as indicated in fig 2 | 2.72 |
| 2 | manhole 2 | as indicated in fig 2 | 2.72 |
| 3 | manhole 1 | 8 additional points around the superstructure | 2.72 |
| 4 | PV-valves | as indicated in fig 2 | 2.72 |
| 5 | PV-valves | as indicated in fig 2 | 5.44 |
| 6 | PV-valves | as indicated in fig 2 | 21.76 |

Table 1: Different measurements performed with their relative parameters

## 2.1 Results and discussion

### 2.1.1 A general overview, measurements 1 & 3

An indication of the relative concentrations around the superstructure can be given by the respective K-values. The first and the third measurement are complementary since in both tests the same source was used under the same conditions, only the immission points were changed. In total results from 18 sampling points were obtained and these give a good overview of the variety in K-values around the accommodation. This is shown in annex figure 3.

The highest K-values can be found on the lee side and for wind directions varying between 30° and 65° from the bow. On the windward side K-values are close to zero. Headwind gives in almost all sample points an average value for K, except for the deck measurement, a location that is situated close to and straight behind the source. Another exception comprises the locations situated near the top of the accommodation such as the inlet accommodation and monkey bridge. Based on these measurements we can deduce that most of the cargo vapors pass around the superstructure, rather than passing over it, even in situations with relatively low wind speeds. Locations like the separation between the gas-safe and the gas-dangerous zone, aft deck 3, inlet engine room and inlet galley all have quite high K-values on the lee side. The relatively higher K-values measured aft of the superstructure at the height of deck 3, indicate that vapors stick to the superstructure while moving up, a result that can be explained as *building-downwash* (citebradstreet). Under a starboard wind between an angle of 30° and 65° from the bow they continue to rise even till the inlet of the accommodations. The inlets of the engine room confirm the presence of higher K-values aft of the superstructure, although these values are always smaller than the ones on deck 3. For this source and for a wind on the beam, 90° from forward, the starboard measurements indicate higher K-values compared to the portside ones. Most probably obstructions on deck at the starboard side change the air flow considerably. However this could not be deduced from our results. Altogether these results suggest that using the manhole for ventilation purposes can lead to high concentrations around the superstructure, especially on the lee side with wind angles between 30° and 65° from the bow.

### 2.1.2 Comparison of two different sources/tanks, measurements 1 & 2

In this section the results of measurement 1 and 2 are compared. The difference between the two measurements is the source location, representing on board a change of tank number. However, in both cases vapor is released through a manhole of identical dimensions. Thus the research question in this case is : what would be the influence on the K-values when the source is 9 m furhter forward and 7.5 m more to the starboard side, as it is in measurement 2, compared to the tank manhole used in measurement 1. Results are shown in figure 4. A general conclusion is that shifting the source further foreward (away from the immission points) results in lower K-values. A transverse shift results in a loss of correlation between the K-values on one side, in this case the starboard side. The reason for this loss of correlation might be the presence of obstructions upstream of the source on the starboard side, namely the catwalk, the manifold and the bulkline. These obstructions might create additional turbulence. Despite the fact that in measurement 2 the source is on the starboard side, vapors are still returned on board with a winddirection from port. It will be clear that bringing the source further foreward has a positive effect on the concentrations measured around the accommodation.

### 2.1.3 Comparison of manhole and PV-valve, measurements 1 & 4

In this part we will compare the venting by the manhole with the venting by the PV-valve, as shown in figure 4. In general, we found that the use of the PV-valve results in the highest K-values with a wind on the bow or 5° to either side. It is important to point out that when using this outlet most of the vapors are lead over the superstructure, as indicated by the immission points 'inlet accommodation' and 'monkey bridge'. The values obtained by venting via the manhole are only half or less of the values of the PV-valve for this specific wind direction. In this situation the ventilation inside the accommodation must be stopped because of the high concentrations near the inlet. In addition, taking the ship's own speed into account, the wind from the bow is a predominant wind direction. For all other wind directions the PV-valve seems a very good solution since no concentration could be found. As mentioned before, the manhole gives significant concentrations on the lee side.

### 2.1.4 PV-valves with higher wind speeds, comparison of measurements 4, 5 & 6

For these measurements only the PV-valves have been used as a source, while keeping the same immission points. The variable parameter in this case was the wind velocity. In measurement number 4 the wind speed was 2.72 m/s at 10 m height, in number 5 the speed was doubled, and in number 6 we used a speed equal to 8 times the original speed of measurement number 4. The evacuation speed of the PV-valves was fixed at 30m/s. Results are shown in figure 5. In all 3 measurements the non-zero concentrations are situated in a sector limited to 20° from the bow on either side. These are again predominant wind directions. With a higher wind speed, as in measurements 5 and 6, the plume does not pass over the superstructure, but passes to both sides of the superstructure.Only with a very light wind, measurement 4, does the main part of the plume pass over the accommodation. Another indication of this phenomenon is given by the results of the immission point on deck. High K-values were measured with high wind speeds, indicating a stack-tip downwash effect (Bradstreet, 1996). With the wind ahead, and independently of the wind speed, significant K-values can be found on the main deck around the superstructure, as well as near the engine room intakes and the intake of the galley. Only the accommodation intake will give lower values with higher wind velocities, thanks to its elevated position. In general we can say that the higher the position of the immission point, the higher the K-values with light wind conditions, while with stronger winds the K-values will decrease. For immission points situated near the main deck, the K-values will be maximum with an intermediate wind force, 5.44 m/s (measurement 2) while both a lower (2.72m/s) or a higher (21.76m/s) wind speed gives lower K-values.

### 2.1.5 Comparison of wind tunnel data with on board measurements

The results from an on-board measuring campaign given in a previous publication (Jacobs et al., 2010) will be compared to the actual corresponding wind tunnel results, namely measurements 1 and 3. The K-values have been converted to concentrations based upon the on-board conditions. The comparison can be found in table 2.

| location | On-board | WT manhole | WT PV-valves |
|---|---|---|---|
| Cargo deck | 28961 | 28415 | 173 |
| Facing | 6230 | 960 | 5367 |
| GDZ PS | 11297 | 15546 | 6925 |
| GDZ SB | 3140 | 2983 | 5309 |
| Intake ER SB | 3920 | 8048 | 4784 |
| Intake AC | 1566 | 1163 | 11026 |

Table 2: Benzene concentrations in $\mu g/m^3$ for on-board measurements during purging operation of a benzene tank by the manhole, wind tunnel(WT) measurements with purging by the manhole and wind tunnel measurements with purging by the PV-valves.

Firstly we will compare the on-board measurements with the windtunnel manhole results. The figures are comparable, except for the facing. Here the windtunnel result is much lower than the on-board concentration. An exact reason for this difference could not be found. Secondly, we suppose that this operation would have been performed using the PV-valves instead of using the manhole as tank outlet. The most important difference is that the resulting concentrations in the accommodation would be 7 to 8 times higher. As explained before, the main reason for this increase is the relative winddirection from the bow which in combination with the PV-valves leads to higher concentrations for immission points situated at higher locations.

# 3 Conclusion

In addition to our on-board concentration measurements (Jacobs et al., 2010) we completed a full set of similar measurements in the Peutz' windtunnel. After optimization of the marine boundary layer in the windtunnel 6 sets of measurements were made. We demonstrated that using a manhole for ventilation purposes leads to relatively high K-values on the lee side, especially for relative wind directions between 30° and 65° from the bow. On the windward side, K-values are close to zero. Using a manhole situated more forward leads to smaller K-values around the superstructure. The most important conclusion is that tank ventilation which makes use of PV-valves leads to high K-values for winddirections from the bow. In this specific case, the use of the manhole gives better results. This was confirmed by comparison with on-board measurements. Nevertheless for all other wind directions the use of the PV-valve is by far the best option. Another important finding is that a higher wind speed does not necessarily mean lower concentrations. With higher wind speeds the stack-tip downwash effect as well as the building downwash effect might occur, resulting in higher K-values near the main deck and number one deck.

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# 5 Appendix

| 2008 | tons | 2010 | tons |
|---|---:|---|---:|
| Methanol | 866,323 | Methanol | 746,141 |
| Sodium hydroxide solution | 359,424 | Sodium hydroxide solution | 380,331 |
| Xylenes | 206,558 | Pentanes | 315,978 |
| Ethanol and ethanol solutions | 149,535 | Xylenes | 161,894 |
| Phosphoric acid | 133,147 | Methyl tert-butyl ether (MTBE) | 159,660 |
| Pentanes | 124,548 | Aromatic free solvents | 155,363 |
| Methyl tert-butyl ether (MTBE) | 119,539 | Ethanol and ethanol solutions | 122,018 |
| Phenol + acetone | 119,065 | Parafines | 111,079 |
| Aromatic free solvents | 111,479 | Phosphoric acid | 91,797 |
| Propane | 107,260 | Phenol | 87,359 |
| Methyl tert-butyl ether (MTBE) | 73,646 | Propane | 84,027 |
| Phenol | 73,040 | Acetone | 73,815 |
| Ammonia | 72,088 | NExBTL | 73,298 |
| Propylene | 66,818 | Phenol + acetone | 72,427 |
| Sulphuric acid | 62,822 | Styrene | 71,934 |
| Butadiene | 60,340 | Benzene | 69,240 |
| Styrene | 59,423 | Formic acid | 68,427 |
| Hexafluorosilicic acid | 57,896 | Butanoles | 67,890 |
| Benzene | 56,841 | Hexafluorosilicic acid | 56,006 |
| Tert-amyl ethyl ether (TAEE) | 54,239 | Ammonia | 51,632 |
| Butane | 53,491 | Ethylene | 45,166 |
| Acetone | 53,074 | Pyrolysis gasoline | 39,426 |

Table 3: Comparison of most carried chemical substances in Finnish ports in 2008 and 2010, tonnes. (Finnish Transport Agency 2012b)

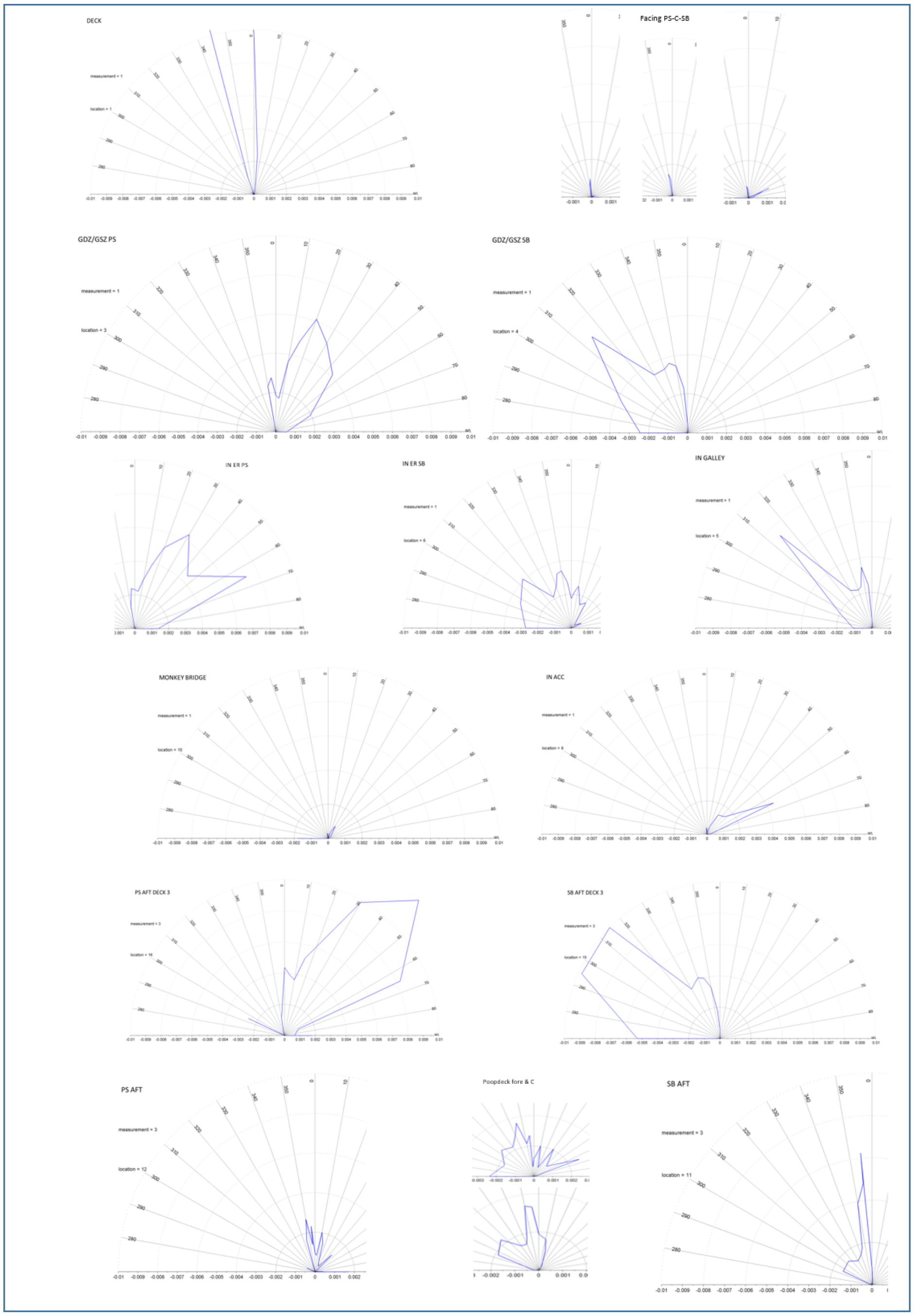

Figure 3: general overview of K-values using manhole 1 for gas-freeing operations

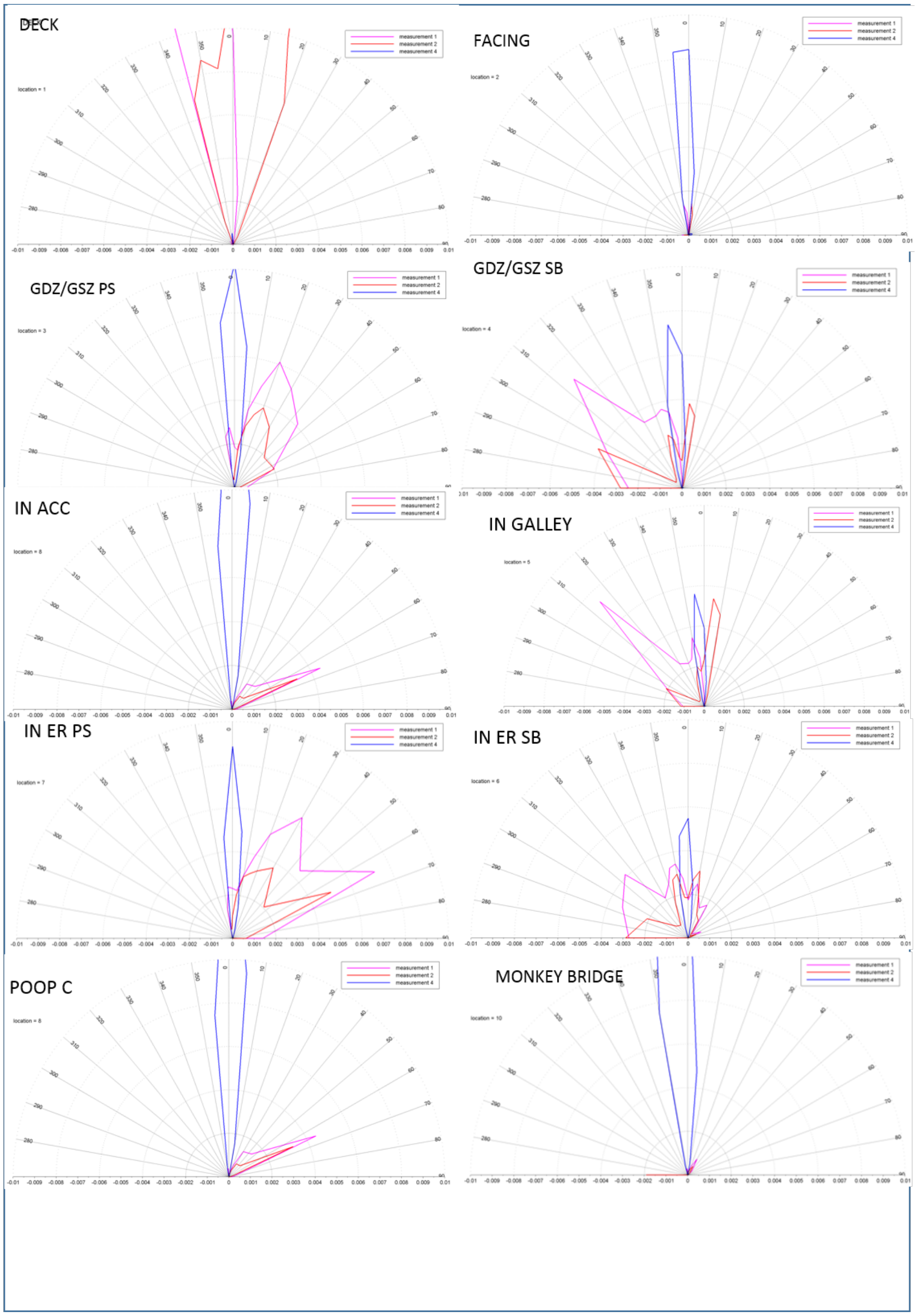

Figure 4: Comparison of K-values for source 1 with source 2 and 4

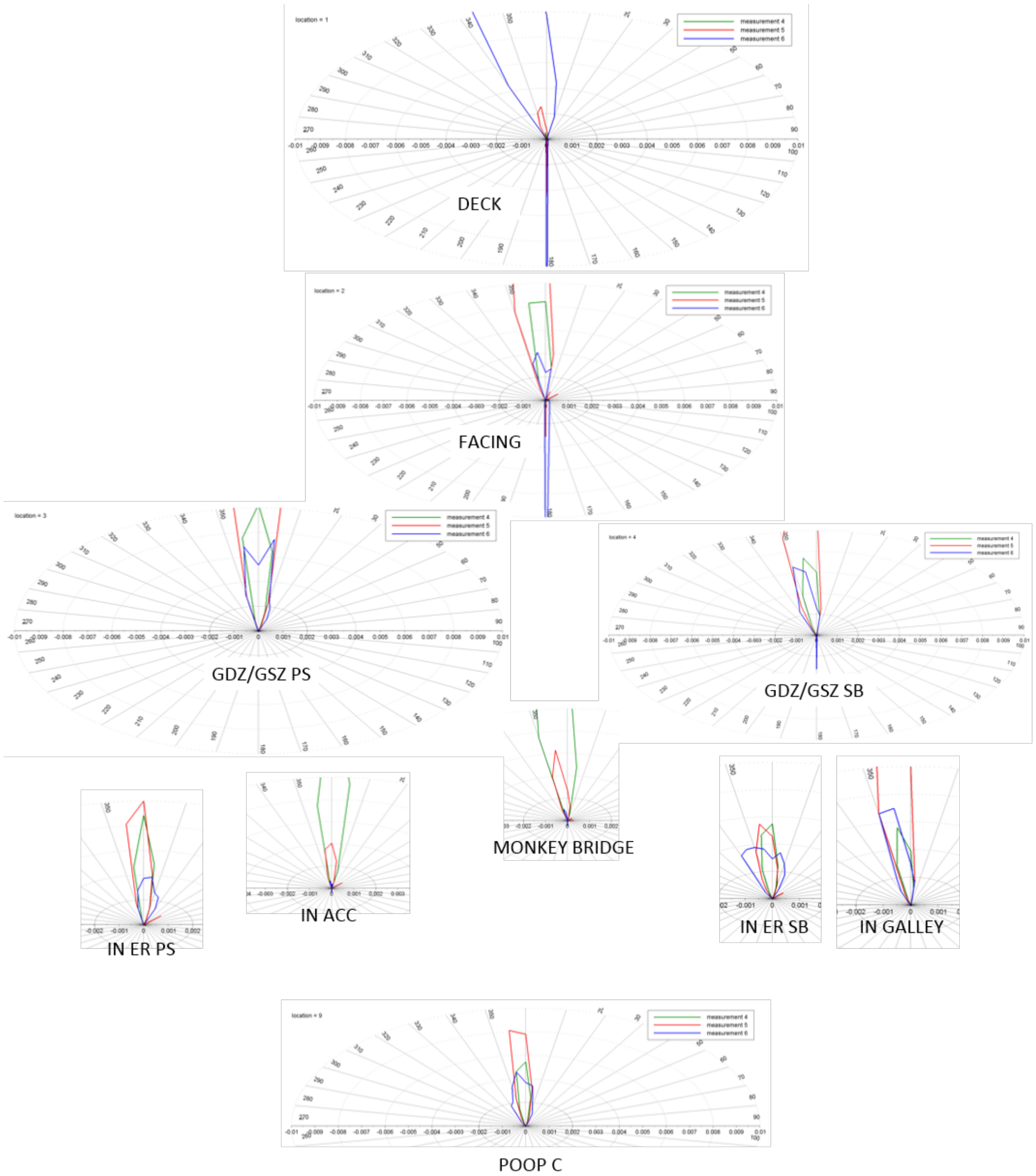

Figure 5: K-values for PV valves under different wind conditions