LDE/LME/LMI Series – dust test

Application note

First Sensor

LDE/LME/LMI Series – dust test

1. Introduction

The physical principle of dynamic or calorimetric type pressure sensors is based on the measurement of a micro flow passing through a flow channel formed inside the sensor package. Due to the fact that gas flow through the sensor is proportional to the applied differential pressure, the sensor can be calibrated and used as a pressure sensor. A bypass connection of the dynamic pressure sensor to the source of differential pressure is typical for many applications. Such sources can be flow tubes, ducts with restrictive elements or velocity probes generating differential pressure as a function of flow. Any time a differential pressure is generated in the source, leakage flow occurs in the bypass, containing the dynamic pressure sensor and connecting tubes. It is obvious that, if the main gas flow contains dust, it is physically possible that dust can be transported to the sensor causing clogging of the micro flow channel and degrading its performance.

The target of this test is to investigate the ability of dynamic type pressure sensors to operate in dusty environments specifically under conditions existing in HVAC systems. It is important to estimate the risk of sensor failure associated with dust clogging and determine conditions of safe operation, long-term stability and possible protection methods in extremely dusty environments. Another target of the test is to compare dust immunity of different dynamic sensors and understand what features of the sensor design can improve its stability in dusty environments.

2. General requirements to the dust test setup

- Operation conditions for the tested sensors should be close to those common in real environments in HVAC systems.
- Concentration and type of dust in the air flow during the tests must be comparable with real HVAC ducts.
- Accelerated dust tests can be performed if volumetric dust concentration and velocity pressure are controlled at intentionally higher levels than during “normal” operation.

It is known that acceptable cleanliness of HVAC ducts is determined by regulatory organizations. For example, the APIRAC association [1] considers that acceptable cleanliness of ducts is achieved when the obtained concentration of surface dust is smaller than 1 g/m^2.

FISIAQ considers two cleanliness classes [2] in new air conditioning ducts: for the P1 class the limit for the concentration of surface dust is 1.0 g/m^2 and for the P2 class the limit is 2.5 g/m^2. In the United Kingdom [2] the maximum limit allowed is 1.0 g/m^2 in supply ducts and 6 g/m^2 in exhaust ducts. Note that dust concentration describing duct cleanliness is given in grams per square meter of duct surface.

When air flows through the ducts, dust particles on the inner surfaces are carried away from their original positions, resulting in particle resuspension, increased volumetric concentration of airborne particles inside the ducts and indoors. Mechanism of dust deposition on the ducts inner surface and dust resuspension into air flow is analyzed in [3].

The level of cleanliness of the closed loop duct used in this dust test can be estimated as (mass of dust)/(area of inner duct surface). It is suggested that by adding an appropriate amount of dust into the closed duct loop, it is possible to create “dirtiness” of the duct essentially exceeding allowable cleanliness level [1, 2]. In this case, an accelerated dust test can be performed. An operating time in the “normal” duct may be equivalent to a shorter operating time in the “dirty” duct multiplied by a factor equal to the ratio of dust cleanliness in the “dirty” and “normal” ducts.

Another factor allowing “accelerated” testing is intentionally higher than “normal” flow though the duct. There are two consequences of high flow. First, a bigger amount of dust is suspended into the air flow volume from the duct walls. It is shown in reference [3] that an increase of flow by a factor of 2, increases the volumetric concentration of dust by a factor of ~10. Second, higher flow creates higher velocity pressure (VP) on a velocity probe. For example if the averaged differential pressure generated by a Pitot-type velocity probe is 100 Pa during typical operation in HVAC systems, and the same pressure during a dust test is 500 Pa, the additional “acceleration factor” is 500/100 = 5. In other words, during the same time interval the air volume passing through the sensor in the test is 5 times bigger than in “normal” operation.

First Sensor

LDE/LME/LMI Series – dust test

3. Dust test setup

The duct loop used in the test is shown in Fig. 1. The loop circulating blower generates an air flow with an air velocity pressure of 100-500 Pa.

All tested dynamic pressure sensors are connected to two velocity probes with 15 cm length, 1/8 inch silicon tubes. The connecting tubes are oriented vertically such that the flow drags dust to the sensors in upward direction.

Figure 1 **Duct loop**

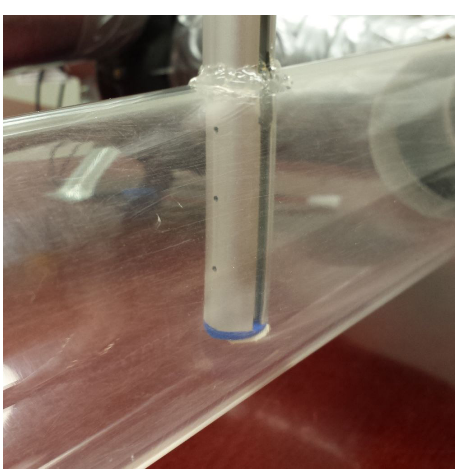

Figure 2 **Pitot-type velocity probe**

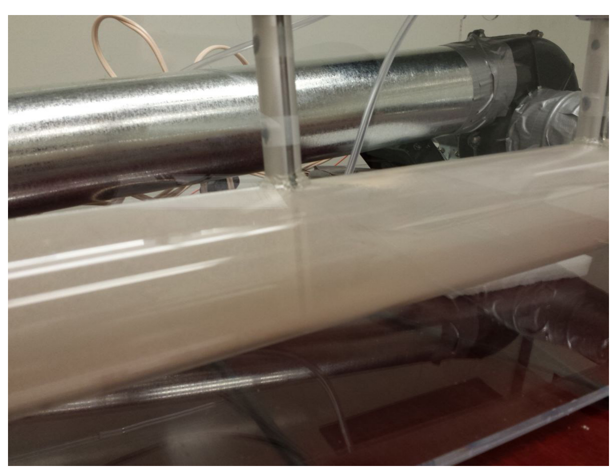

Figure 3 **Dust inside the duct during operation**

LDE/LME/LMI Series – dust test

3.1 Type of test dust

Two types of dust were used in the test. ASHRAE Test Dust #2 was used at the beginning of the test. Unfortunately, lint contained in this dust caused clogging of the blower wheel and the duct loop had to be opened for cleaning.

SAE fine test dust was added to the dust loop after the first ~300 hours of the test. SAE dust does not contain lint which allowed the system to run for a long time without blower cleaning.

ISO 12103-1, A2 fine test dust

Chemical ingredient	CAS number	% of weight
SiO_2	14808-60-7	68 – 76
Al_2O_3	1344-28-1	10 – 15
Fe_2O_3	1309-37-1	2 – 5
Na_2O	1313-59-3	2 – 4
CaO	1305-78-8	2 – 5
MgO	1309-48-4	1 – 2
TiO_2	13463-67-7	0.5 – 1.0
K_2O	12136-45-7	2 – 5

Table 1: Composition of SAE fine test dust

ISO 12103-1, A2 fine test dust

Micron size	Cumulative volume % less than
1	2.6
2	11.2
3	19.8
4	27.3
5	33.7
7	43.8
10	54.0
20	72.0
40	90.9
80	99.6
120	100.0

Table 2: Dust particles size volume distribution of SAE fine test dust

LDE/LME/LMI Series – dust test

4 Test #1 – preliminary test with ASHRAE Test dust #2

4.1 Sensors under test

- Sensors #1.1 and #1.2
- Sensor #2
- Sensor #3
- Sensor #4
- Sensor #5

- First Sensor LDES500UF6S (500 Pa)
  - With filter, 90 µm pores (filter 2)
  - With filter, 20 µm pores (filter 4)
  - No filter

4.2 Test procedure

First amount of dust added to the loop was about 42 g. Equivalent surface dust concentration on the inner surface of the duct was about 56 g/m^2, which is about 60 times dirtier than in dirty (allowable) real ducts.

All sensors were connected to two velocity probes (see Fig. 4). The sensors were positioned such that their ports were oriented vertically downward. The length of the vertical connecting 3 mm ID tubing was about 15 cm.

The velocity pressure (VP) generated in the system at the beginning of the test was about 250 Pa. The blower was stopped at 96 h, 168 h and 238 h after the beginning of the test and all the sensors were re-measured.

It was found that VP dropped to about 120 Pa though the supply voltage for the blower was constant during the test. After 238 h, the duct loop was disassembled. The blower wheel was found clogged with the agglomerate of lint and dust that reduced air flow and therefore VP. After the blower wheel was cleaned, additional amount of 15 g of dust was added into the duct loop. Total amount of loaded dust reached 57 g (dust concentration of about 76 g/m^2) with less than 5 g of dust agglomerate removed during cleaning. VP was increased to about 375 Pa – with the same supply voltage applied to the blower. The test was continued for the next 66 h with total accumulated time of 304 h.

The most significant changes of sensitivity of the sensors under test were registered namely after adding of the new portion of dust and increasing of VP.

4.3 Observations

A process of agglomeration of dust at very high dust concentrations was observed during the test. Agglomerations of lint were clogging the blower wheel and had to be removed. As a result, composition of dust was varying during the test. It may be expected that small dust particles also form agglomerates resulting in an increase of the effective duct particle size. Dust concentration in the flow and its composition are determined by dynamic balance of two processes – deposition of dust on the duct surfaces and resuspension of dust back into the flow. Agglomeration of dust and its deposition on the walls of the duct, the blades of the blower wheel and the gaps in the joints may result in reduction of volumetric dust concentration in the air flow with time.

LDE/LME/LMI Series – dust test

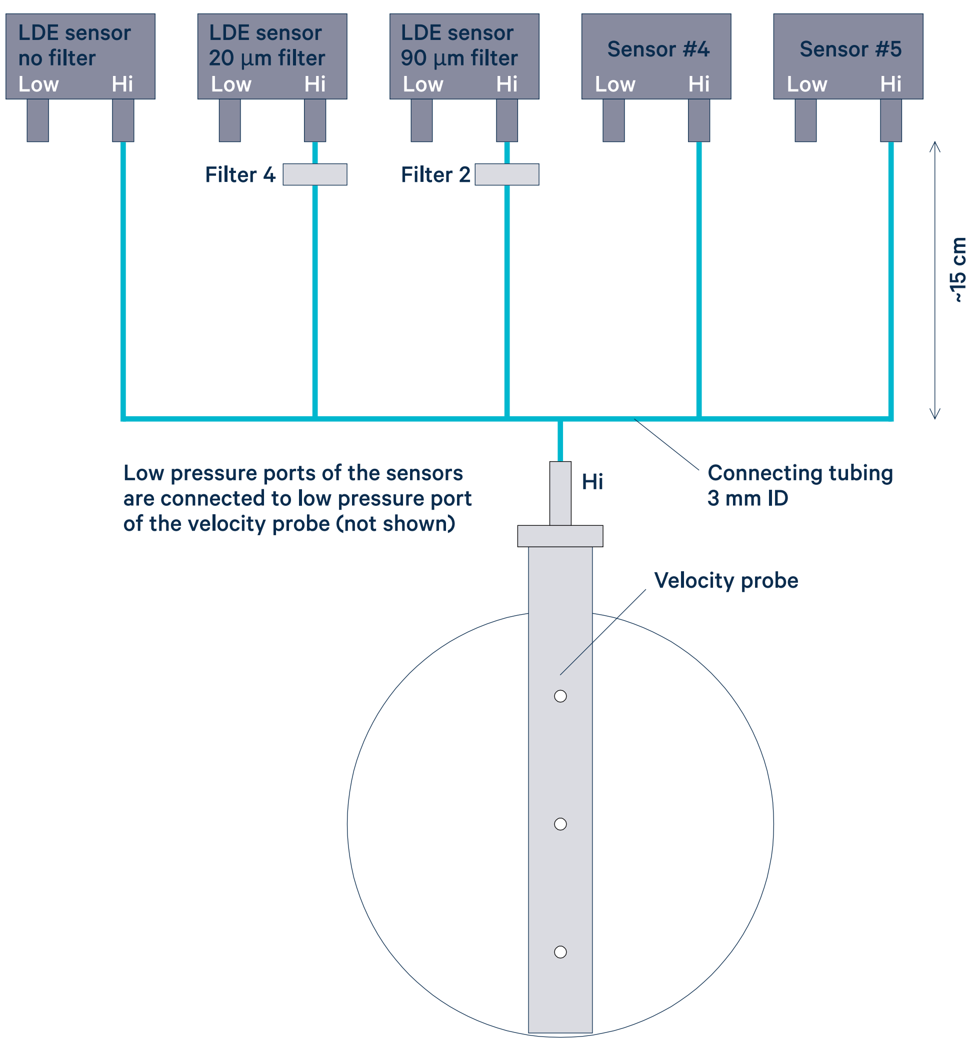

Figure 4 **Connections of the sensors to the velocity probe**

LDE/LME/LMI Series – dust test

4.4 Test results

LDE sensors from First Sensor
The normalized sensitivity of the LDE sensors is shown in Fig. 5.

Filter 2 contains 1.59 mm thick and 10 mm ID layer of porous plastic material from GenPore (www.genpore.com) with 90 µm pores. Filter 4 contains GenPore plastic layer of the same thickness, 12 mm ID and pores of 20 µm.

Pneumatic resistance of the filters was ~12 Pa·s/ml for filter 2 and ~35 Pa·s/ml for filter 4. This resistance is significantly lower than pneumatic resistance of LDE sensors ~50,000 Pa·s/ml for 500 Pa sensor.

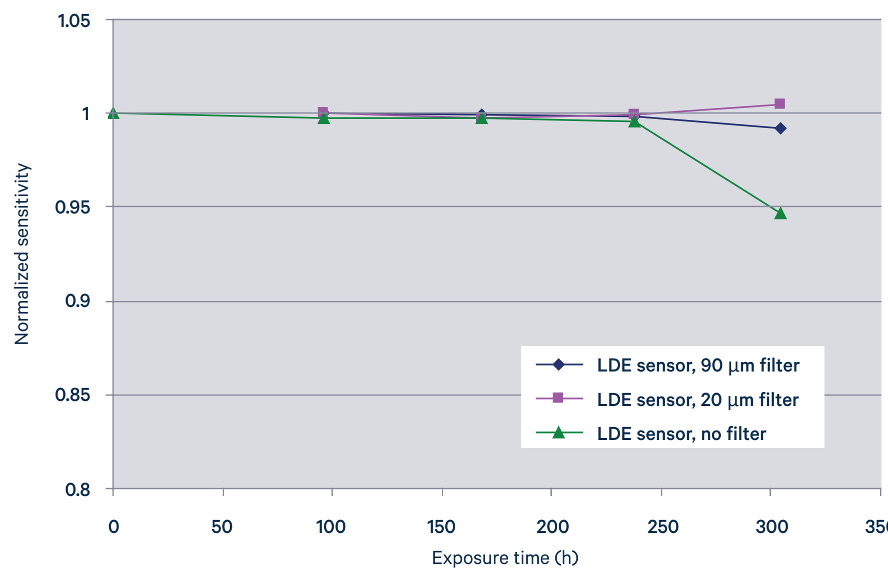

Figure 5 **Sensitivity of LDE sensors during dust test**

Sensors #1.1 and #1.2
The sensors #1.1 and #1.2 were tested. The sensitivity of the sensor #1.1 was varying during the test, reducing to below 90 % of the initial sensitivity (Fig. 6).

The sensor #1.2 demonstrated a much less stable operation. Its sensitivity after 168 hours of test was less than 80 % of its initial sensitivity. During re-measuring procedure, the sensitivity of the sensor dropped to zero. The sensor was replaced by another new one, #1.2 (2). The sensitivity of the new sensor dropped to less than 7 % of the initial sensitivity during the test.

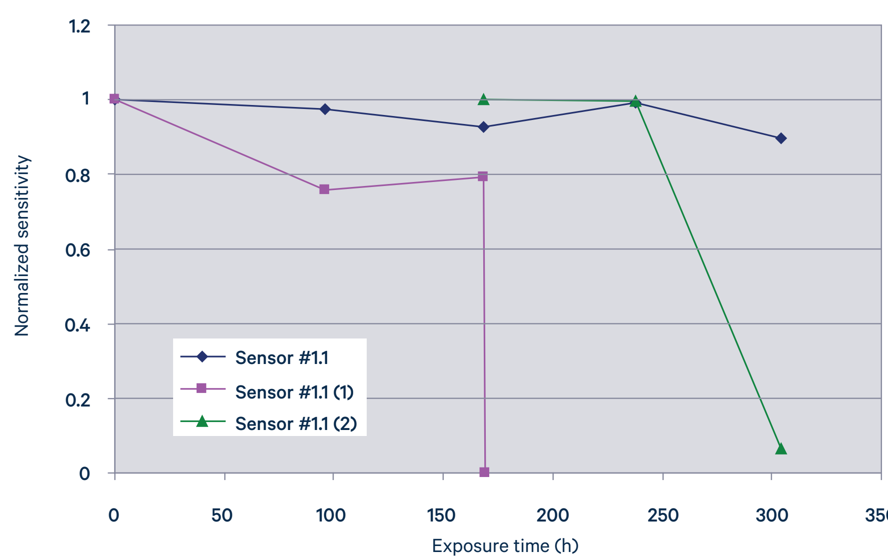

Figure 6 **Sensitivity of sensors #1.1 and #1.2 during dust test**

LDE/LME/LMI Series – dust test

Sensor #2

The pressure response of sensor #2 is non-linear. Its variations during dust test are shown on in Fig. 7. The sensitivity of the sensor was calculated in a 0-200 Pa sub-range where the pressure response was more linear. The drift of sensitivity which reached about 35 % of its initial value is shown on in Fig. 8.

After 304 hours of dust test, the sensor was pneumatically "cleaned". Air compressed with 35 ml syringe (about 0.5 bar) was applied to one port of the sensor and dust was blown away. A clearly visible cloud of dust was blown out during "cleaning" procedure. The sensitivity of the sensor was almost restored to its initial value (dashed line on Fig. 7).

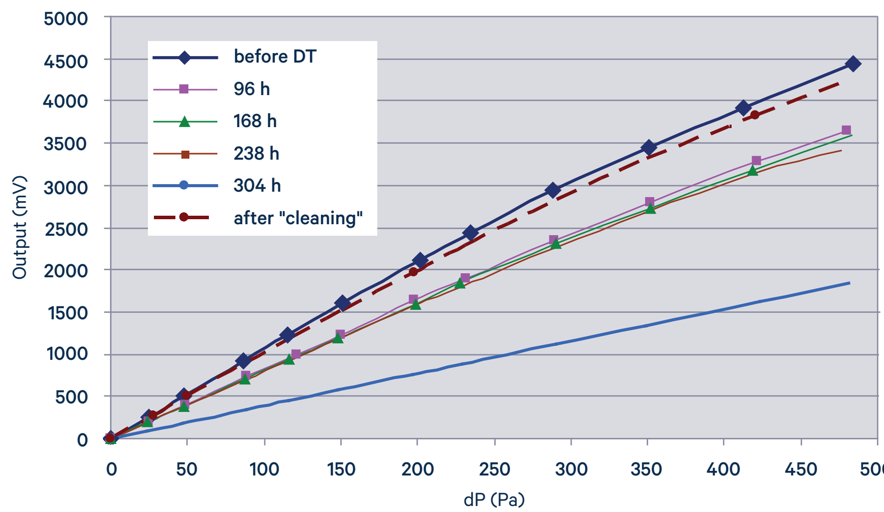

Figure 7 **Pressure response of sensor #2 during dust test**

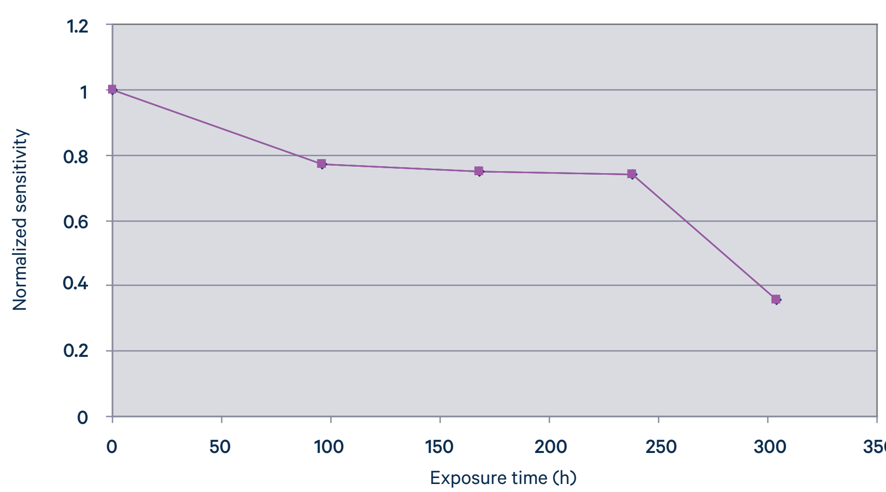

Figure 8 **Sensitivity of sensor #2 during dust test**

LDE/LME/LMI Series – dust test

Sensor #3

The sensitivity of sensor #3 during dust test is shown on in Fig. 9. Sensitivity of the sensor reduced to ~60 % of the initial value after 304 hours of the test.

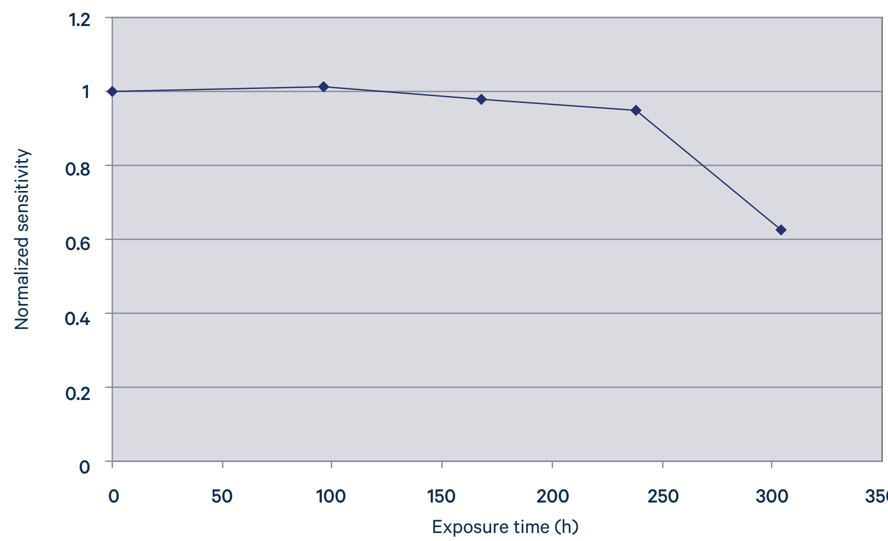

Figure 9 **Sensitivity of sensor #3 during dust test**

LDE/LME/LMI Series – dust test

Sensor #4
The sensitivity drift of sensor #4 is shown on in Fig. 10. The sensor demonstrated good stability during the first 238 hours, then its sensitivity dropped by about 30 %.

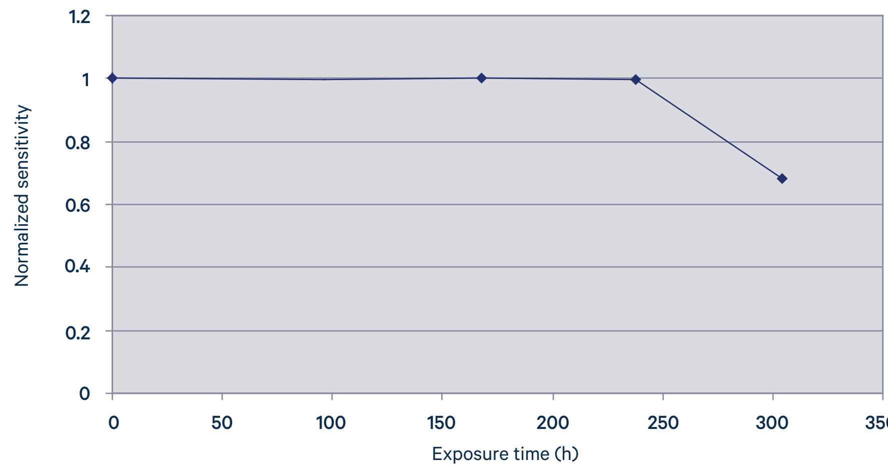

Figure 10 **Sensitivity of sensor #4 during dust test**

Sensor #5
Fig. 11 shows variations of pressure response of sensor #5 during dust test.

Pneumatic “cleaning” performed after 304 hours of test almost restored the initial sensitivity of the sensor (dashed line on Fig. 11).

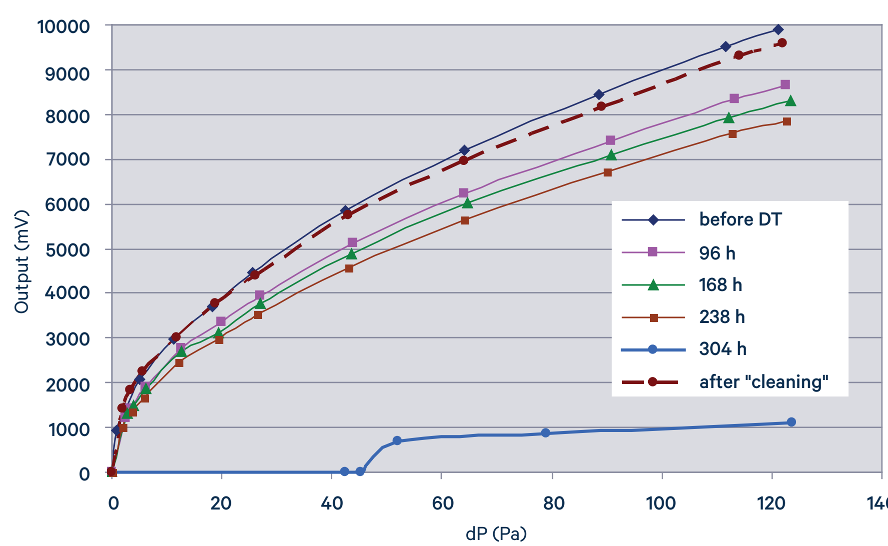

Figure 11 **Pressure response of sensor #5 during dust test**

LDE/LME/LMI Series – dust test

4.5 Analysis of the results

Fig. 12 presents the drift of normalized sensitivity caused by dust clogging for several of the most stable sensors.

By creating high dust concentration and high velocity pressure in the duct loop, it became possible to adversely affect all sensors except the LDES500 sensor protected with dust filter 4. The pneumatic resistance of this filter is about 0.07 % of the resistance of the LDES500 sensor. Dust clogging of the filter, which may increase its resistance a few times, does not affect the pressure sensitivity of the LDE sensors significantly.

The LDES500 sensor with the highest pneumatic resistance of ~50,000 Pa·s/ml demonstrates better immunity to dust clogging than all other tested sensors. Connecting a filter to the LDE sensor further improves its dust immunity.

The usage of dust filters is problematic for the sensors with low pneumatic resistance due to essential reduction of their pressure sensitivity after filter connection and instability of sensitivity caused by filter clogging.

The pneumatic resistance of filter 2 is ~35 Pa·s/ml. Compared with the LDE sensor, the resistance of the filter is more than 1400 times less than the sensor resistance. The very high pneumatic resistance of the LDE type sensors allows the usage of dust filters for effective protection against fine dust.

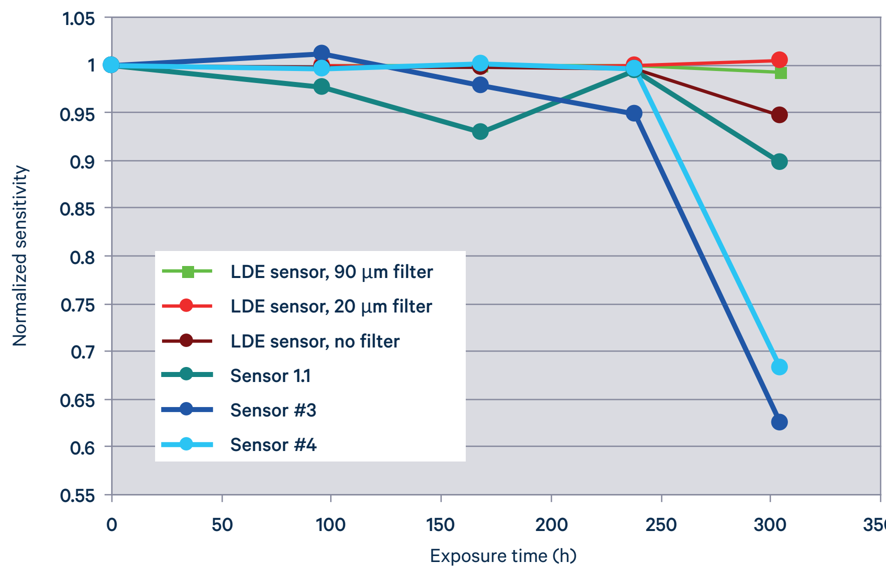

Figure 12 **Normalized sensitivity of the sensors during dust test**

LDE/LME/LMI Series – dust test

5 Test #2 – high dust, high flow test

5.1 Sensors under test

New sensors #1.1 and #3 were used in this long term test. The sensors #2 and #4 were pneumatically cleaned as was described above. The sensitivity of sensor #2 was restored up to 94 % of its initial sensitivity. The sensitivity of sensor #4 reached 95 % of the initial sensitivity after pneumatic cleaning.

Two new samples of LDES500UF6S (500 Pa) were used in the test:

- with filter with 20 µm pores (filter 4)
- without filter protection.

Sensors 1.2 were excluded from this dust test because of their poor, unstable behavior in dusty environments (see results of preliminary test). Sensor #5 was also excluded from the test.

5.2 Test procedure

At the beginning of the test (after blower wheel cleaning), SAE fine test dust was added to the system such that total dust weight in the loop reached 77 g or 103 g/cm^2.

After 449 and 984 hours of the test, additional portions of 10 g of dust were added, and total dust concentration reached 116 g/cm^2 and 129 g/cm^2 correspondingly.

Constant velocity pressure (VP) of 500 Pa was maintained during the test.

5.3 Accelerated aging factor

The surface dust concentration of more than 100 g/cm^2 used in the test exceeds allowable concentration by a factor of 100-130.

The second factor, is velocity pressure (VP). A VP of 500 Pa was maintained during the test. It is assumed that this pressure is at least 5 times higher than the averaged operating pressure existing in the ducts during real operation. The higher pressure results in bigger volume of air passing through the sensors and therefore 5 times faster dust clogging.

The third factor is related to the amount of dust "resuspended" from the duct walls into the air volume. The effect of resuspension depends on air velocity. It was shown (ref[3, Fig.10]) that the reduction of flow through the duct by a factor of ~2 results in a ~10 times lower volumetric dust concentration. Therefore, it can be assumed that at normal operation, two times lower flow (4 times lower velocity pressure) generates ~10 times lower dust concentration than those used at present dust conditions.

Based on the assumptions that

- "dirtiness" of the duct is ~100-130 times higher than maximum allowable;
- leakage through the sensor connected in the bypass to the velocity probe is ~5 times higher than during typical operation;
- additional volumetric dust concentration increase factor caused by high flow is ~10,

we estimate that the accelerated aging factor of the dust test is about $100 \cdot 5 \cdot 10 = 5000$.

In other words, 1000 hours of the test are equivalent to ~500 years of operation in HVAC systems.

It is possible that at high levels of dust concentration, agglomeration of dust particles occurs, and smaller size particles stick to each other building agglomerates with bigger size. As the result, concentration of fine dust may be reduced in time. For compensation of this effect, fresh dust was added into the duct loop periodically.

For indirect confirmation of high dust concentration in the air flow during the test, the rate of clogging of the sensors with poor dust immunity can be used as an indicator (see Fig. 13).

LDE/LME/LMI Series – dust test

5.4 Test results

Fig. 13 shows variations of the sensors sensitivity during dust test.

The sensitivity of the sensors #1.1, #2 and #3 changed essentially during the dust test. These sensors were pneumatically cleaned periodically. Cleaning procedures marked by red arrows resulted in partial restoring of their sensitivity.

Note that the sensor #3 demonstrated unexpected clogging-related increase of sensitivity during the first 168 hours. After the first cleaning procedure, dust clogging resulted in a sensitivity decrease which was typical for all other sensors.

The sensor #4 demonstrated better stability though its sensitivity dropped below 60 % of its initial value in 1240 hours.

Fig. 14 shows the variation of sensitivity for two LDES500UF6S sensors (with and without filter). The sensor #4 data are presented for comparison.

It was confirmed that filters provide a high level of dust protection. No drift of sensitivity was detected for the filter-protected LDE sensor – within sensitivity measurement errors of ±0.3 % (caused by repeatability of the calibration system).

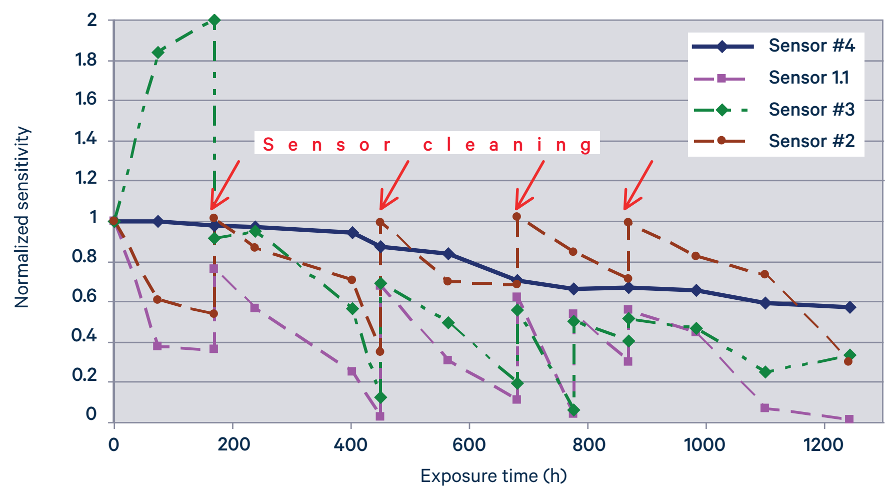

Figure 13 **Sensitivity variations due to dust clogging of the sensors**

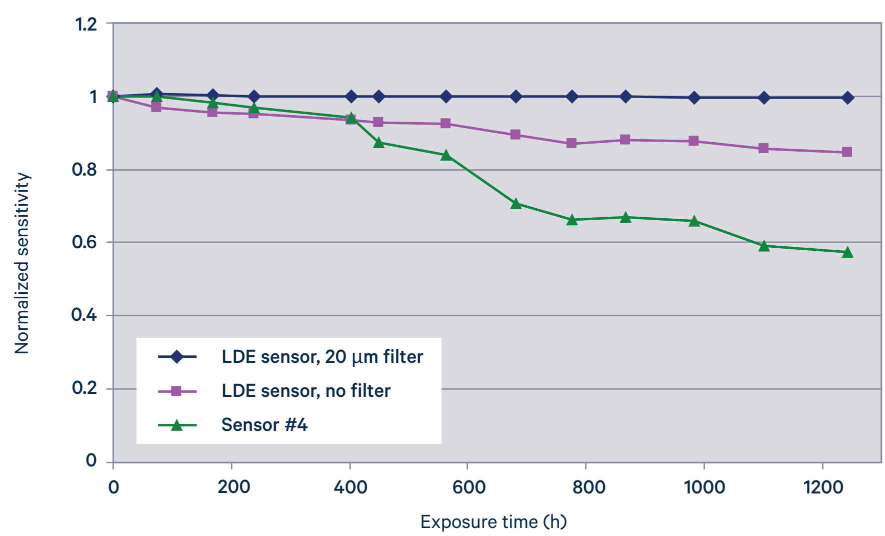

Figure 14 **Sensitivity variations of LDES500UF6S sensors**

LDE/LME/LMI Series – dust test

5.5 Testing of glass fiber filters with LDE sensors

The effectiveness of filter protection stimulated additional tests with new filters:
- Glass fiber filter APFA
- Glass fiber filter APFD

These standard filters are produced by Millipore. Their specification can be found on: http://www.emdmillipore.com/CA/en/product/Glass-%26-Quartz-Fiber-Filters,MM_NF-C255#specifications

Disks with diameters of ~1 cm were cut from the filter material and placed in cartridges (see Fig. 15).

Two new LDES500UF6S and two LDES050UF6S (50 Pa sensors with lower pneumatic resistance) sensors with APFA and APFD glass fiber filters 5-8 (see Fig. 16) were connected to the dust test setup after 776 hours of running test. During the next ~470 hours of operation, these sensors demonstrated no drift of sensitivity (within repeatability error of measurement system).

Figure 15 **Glass fiber filters**

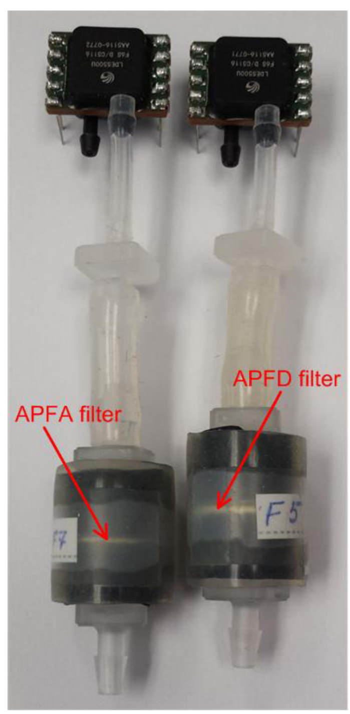

Figure 16 **Filters in cartridges connected to sensors**

LDE/LME/LMI Series – dust test

5.6 Filters and pneumatic resistance of the sensors

A dust filter connected in series to the sensor may potentially adversely affect its performance. Fig. 17 schematically shows the connection of the filter and tubing to the sensor.

The source of differential pressure generates an air flow passing through the contour which includes connecting tubing, the filter and the sensor itself. All components of this contour have non-zero pneumatic resistance. Therefore, pressure drop across each component is inevitable. As a result, the pressure drop across the sensor (actually measured pressure) is always lower than the pressure of the source. The difference between these two pressures can be minimized if the pneumatic resistance of the sensor is much higher than the resistance of the tubing and the filter.

The very high pneumatic resistance of the LDES500UF6S sensor practically eliminates the influence of connected tubing and filters on its sensitivity. In fact, factory calibrated pressure sensitivity (scale factor) stays unchanged if the user connects "reasonably" long tubing and filters with acceptable resistance. Connection of the same components in series to the sensors with 100 times less resistance creates problems due to the reduction of pressure sensitivity.

An additional problem is the increase of filter resistance due to dust loading during operation life time. The effect of dust loading is described for example in article [4]. Dust loading results in an increase of the filter resistance and therefore reduction of the sensitivity of the pressure sensor.

It should be noted that high pneumatic resistance of the sensor has "doubled" the positive effect in maintaining of stable operation when the filter changes its resistance. First, the contribution of the increase of the filter resistance to the sensors pressure response is inversely proportional to the sensor resistance. Second, volume of air passing through the sensor and the filter and therefore the amount of dust accumulating on the filter are also inversely proportional to the sensor resistance. In other words, the filter stays "cleaner" when it is connected to the sensor with high resistance, and the change of its resistance is relatively smaller compared to the high resistance of the sensor.

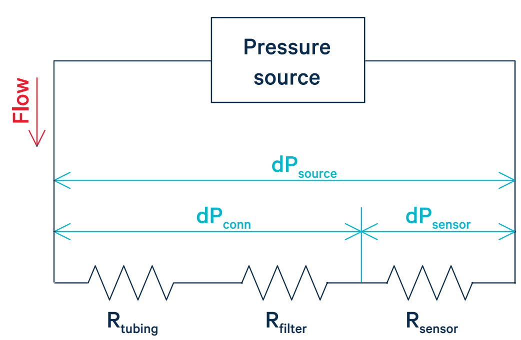

Figure 17 **Pneumatic scheme of the sensor connection**

Component	Resistance (Pa·s/ml)	Note
Sensor #1.1	135	
Sensor #1.2	280	
Sensor #2	620	
Sensor #3	170	
Sensor #4	4300	
Sensor #5	6200	
LDES500UF6S	50000	
Filter 4	35	0.07 % of LDES500UF6S
Filter 5	52	0.1 % of LDES500UF6S
Filter 6	48	0.37 % of LDES050UF6S
Filter 7	85	0.17 % of LDES500UF6S
Filter 8	79	0.6 % of LDES050UF6S
1 m tubing with 3 mm ID	4.5	
1 m tubing with 5 mm ID	0.6	

Table 3: Pneumatic resistance of the components used in dust test.

LDE/LME/LMI Series – dust test

6 Test #2 – high dust, normal flow test

6.1 Sensors under test

- Sensors #2
- Sensors #4
- LDES500UF6S (500Pa)
- LMIS500UB3S (500Pa)

Two new sensors of #1.1 and #1.2 were connected to the test system after 389 hours from the beginning of the test.

All sensors were operated without dust filters.

6.2 Test procedure

Though very high dust concentration requires usage of dust filters to protect the sensors, there is a possibility of flawless operation of dynamic pressure sensors without filters when dust concentration is low or moderate. Operation of the sensors without filters was tested at less aggressive conditions which are closer to real operating conditions in HVAC applications.

Circulating flow in the duct loop was reduced approximately two times such that velocity pressure dropped from 500 Pa to 125 Pa. This was considered to be a typically average operating pressure in HVAC systems. As a result, leakage through the sensors was reduced by 4 times and volumetric dust concentration was reduced by ~10 times compared to previous tests.

Portions of fresh SAE fine dust were added into the duct loop during the test with the following schedule:
10 g at the beginning of the test;
5 g after 231 hours;
7 g after 462 hours;
5 g after 532 hours;
7 g after 764 hours;
5 g after 1,119 hours.

The mass of loaded dust was increased from 107 g to 136 g causing an increase of surface dust concentration from 143 g/m^2 to 181 g/m^2.

For the new test:
- “dirtiness” of the duct is ~150 times higher than maximum allowable;
- leakage through the sensor connected in bypass to the velocity probe is approximately the same as during typical operation;
- no additional volumetric dust concentration increase compared to typical operation.

Estimated accelerated aging factor is about 150. In other words, 1000 hours of the test are equivalent to ~17 years of operation in HVAC systems.

First Sensor

LDE/LME/LMI Series – dust test

6.3 Test results

The drift of the sensor sensitivity during the test with moderate dust concentration is shown on Fig. 18.

The LMI and LDE sensors with the highest pneumatic resistance demonstrated no measurable drift of sensitivity. All other tested sensors demonstrated significant sensitivity drifts with reductions of 6-40 %.

The duration of the test of 1257 hours is equivalent to 21 years of normal operation in HVAC systems.

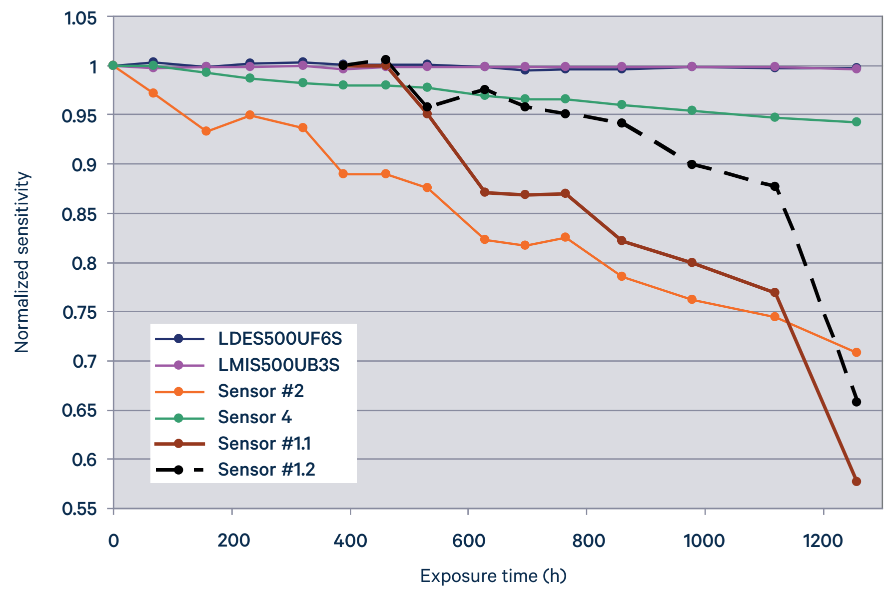

Figure 18 **Sensitivity variations during the test with moderate dust concentration**

First Sensor

LDE/LME/LMI Series – dust test

7 Conclusions

7.1 High-dust, normal-flow operation

- Sensors were tested without the use of external particulate filters.
- First Sensor sensors experienced no measurable sensitivity drift during testing period equivalent to ~21 years of normal operating conditions.
- Sensitivity reduction of competitor products ranged from 6 % up to 40 % over the course of the experiment.

7.1 High-dust, high-flow operation

- Compared to the best competitor sensor, the unfiltered LDE sensor experienced lower sensitivity drift during testing (~15 % vs. ~40 % after 1,200 hours).
- The filtered LDE sensor experienced no measurable sensitivity drift during the equivalent of ~600 years of normal operation.

8 General observations

- Pneumatic resistance – or the sensors resistance to flow – is the largest predictor of sensor stability in highly contaminated ducts.
  - On average, First Sensor sensors have a pneumatic resistance which is 100 times higher than competitor products.
- High pneumatic resistance results in the reduction of air velocity in connecting tubing. This aids in gravity trapping larger particle sizes prior to entry of the sensor flow channel.
- Dust filters may be required in the most extremely contaminated conditions.
  - In general, introduction of a filter results in slight reduction of sensor sensitivity.
  - Prolonged exposure to dust can clog the filter, which leads to a further reduction in pressure sensitivity.
  - High pneumatic resistance of a sensor is imperative to minimize performance degradation due to usage of dust filters.

References

1. APIRAC – Avaliação, Limpeza & Restauro de sistemas AVAC (ALR 2004). Lisboa: APIRAC, 2004.
2. Holopainen, R. et al – Effectiveness of duct cleaning methods on newly installed duct surfaces. Indoor Air, Vol. 13 (2003) 212-222.
3. B. Zhou, B. Zhao, Z. Tan – How Particle Resuspension from Inner Surfaces of Ventilation Ducts Affects Indoor Air Quality – A Modeling Analysis, Aerosol Science and Technology, 45:996–1009, 2011, DOI: 10.1080/02786826.2011.576281.
4. W. Hinds, N. Kadrichu The Effect of Dust Loading on Penetration and Resistance of Glass Fiber Filters, Aerosol Science and Technology 27:2 (1997), pp.162-173.