Evaluation of air flow distribution within the design of SMART emission monitoring device

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Abstract Air quality is one of the fundamental parameters in the prospect of a healthy and thriving city environment. With the upcoming tightening of regulations for pollutions in general, it is necessary to provide and access real-time data regarding to the air quality and presence of pollutants within the smart city. The article aims on improving the design of an existing design of an emission monitoring device in previous research. A CFD model was built in Ansys Fluent 2022 R2 consisting of four smart emission sensors, from which the key improvements in terms of air flow characteristics were retrieved from. The article presents a redesign of the flow channels to improve air distribution. Although the pressure loss has increased by 8%, all four sensors show 5.66 m/s air flow with 12 Pa setting of the fan. In conclusion, a physical model of the redesigned geometry must be built and analyzed using PIV methodology with particle flow measurement.

1 Emissions and air quality

Air quality is one of the most critical characteristics that can catalyst either a large sum of diseases, sicknesses or provide healthy environments for people to thrive in. Several fundamental substances exist according to the EÚ that must be monitored with the city, which are PM_{2.5} / PM_{10} (Particulate Matter – Dust), N_{2}O (Nitrous Oxides), O_{3} (Ozone) and S_{2}O (Sulphur Dioxide) (1). For instance, according to the European Air Quality Index, the cleanest index category from 0 – 10 is accompanied with the following measured concentrations:

<table>
<thead>
<tr>
<th>EAQI</th>
<th>Quality</th>
<th>PM_{2.5}</th>
<th>PM_{10}</th>
<th>N_{2}O</th>
<th>O_{3}</th>
<th>S_{2}O</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 10</td>
<td>Very good</td>
<td>0 – 10</td>
<td>0 – 20</td>
<td>0 – 40</td>
<td>0 – 50</td>
<td>0 – 100</td>
</tr>
<tr>
<td>20 – 25</td>
<td>Moderate</td>
<td>20 – 25</td>
<td>40 – 50</td>
<td>90 – 120</td>
<td>100 – 130</td>
<td>200 – 350</td>
</tr>
<tr>
<td>&gt; 100</td>
<td>Extremely poor</td>
<td>75 – 800</td>
<td>150 – 1200</td>
<td>340 – 1000</td>
<td>380 – 800</td>
<td>750 – 1250</td>
</tr>
</tbody>
</table>

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Based on other emission indexes, substances such as CO (Carbon Monoxide), CO$_2$ (Carbon dioxide) and CH$_4$ (Methane) are incorporated.

2 Wireless emission monitoring system

One of the largest downfalls in progress is the lack of relevant data of emissions in real time. In current situation, data is provided by lengthy manual boiler inspections, which require trained personnel, which is both expensive and simply not frequent enough to take effective action towards building a clean environment. On this note, one of the solutions would be to design of designing a low-cost monitoring device that can be attached to the chimneys of heat sources and wirelessly transmit measured data 24/7 with minimum maintenance. Figure 1 shows the seven main parts of the prototype to fulfil its functionality.

![Fig. 1. Electrical components of wireless monitoring device: 1. Arduino WiFi Rev2, 2. Telecommunication module GPRS, Thermocouple MAX6675, 4. PM sensor PMS5003, 5. MQ series emission sensors (CO, O$_3$, S$_2$O), 6. Li-on Battery, 7. Fan. (2)](image)

Figure 2 illustrates both the CAD design and build of the prototype. Please not, the article will not dive into the electrical architecture and the programming itself, as the focus is the computational fluid dynamic model within the device.

![Fig. 2. Illustrations of the wireless monitoring device: 1. CAD model, 2. Electrical architecture consisting of all parts.](image)
3 CFD model of wireless monitoring device

3.1 Pre-processing of the CFD Model

A successful design prototype must incorporate and validate design requirements in order to check if the design will work as planned. After demonstrating a “proof-of-concept”, a Computational Fluid Dynamic (CFD) model shall be built of the wireless monitoring device. The design has several critical requirements relating to sufficient air flow, maximum temperature of air and preventing condensation of moisture within the tube. A quick summary of the main design requirements (used for the CFD model) are presented below:

Three important parameters and characteristics that must be evaluated in the monitoring device:

(A) The drop in air pressure between the inlet and the outlet (expresses how efficiently the air flows)
(B) The air flow in the proximity of the air quality sensors (placed in four different locations)
(C) The average volume flow rate (amount of time taken for measurement volume to be replenished with “new” air)

The goal of the simulations is to provide feedback to the design of the monitoring device and allow to evaluate a modified design. The chosen tool is Ansys Fluent 2022 R2 based on numerous scientific publications such as modelling of greenhouse gas emissions from industrial plants (3). Another example of how Ansys Fluent is used in practice of simulation of emissions is presented by Ansys corporation (4). The first step in building the CFD model constitutes of the geometry definition. The first model will constitute four air quality sensors (the PMS5003 – Measuring PM, MQ7 – Measuring CO concentrations, MQ135 –Measuring VOC concentrations, MH-Z19 – Measuring the CO2 concentrations) (5) (6) (7) (8). Measuring body placed in the center of the device. It is assumed that the pipe is 20mm in diameter and 200 mm of length. The fan is assumed to be 80 mm in diameter.

Fig. 3. Ansys geometry definition of emission monitoring device with four smart sensors
The average sizing of the elements is 10 mm. Inflation was used on the inlet pipe to increase the mesh density at the wall boundary. This leads to a total element count of 876 242 and node count of 1 245 900. The mesh at the proximities of the sensors is also made denser as illustrated in figure 4.

Fig. 4. Graphical representation of mesh in ANSYS FLUENT 2022 R2

The inlet was set as a “free pressure inlet” and the outlet was set with an absolute pressure (due to the fan) of 12 Pa (2). The wall is assumed static with no movement. The solver was set to take energy and viscosity (K-epsilon model) in account to simulate the pressure losses during turbulent flow from the inlet towards the outlet.

3.2 Pre-iteration CFD results

Figure 5 depicts the flow characteristics on the original geometry (X-Z plane). The air flow through the inlet at 12 Pa pressure is 4.59 m/s. This equates to a flow rate of 1.44 L/s. This represents 66% air exchange per second. The design shows reverse flow, which must be minimized in the redesign of the geometry. The reason behind this is that the emission particles however follow iso-lines within the pressure field, therefore, the reverse flow should be minimized to avoid accumulation of pollutants within the measuring chamber.
Fig. 5. Flow characteristics of the original geometry: 1. Velocity contour plot 2. Flow path-lines

Figure 6 show the air velocities in the planes the sensors are placed. In general, the flow distribution is significantly lacking, and the sensors are not able have a representative sample of air realistic to the outside ambient conditions. Significant redesign is necessary.

Fig. 6. Velocity contour plot in flow direction: Sensors 1. PMS 5003. 2. MQ-135. 3. MQ-7. 4. MH-Z19

4 Redesign of monitoring device

The redesign of the monitoring chamber must consider following improvements:

a) Improving a flow distribution
b) Decreasing a flow reversal
c) Potential increase of an inlet velocity (indicating lower pressure losses in device)

The way the geometry was modified can be divided into two main parts. The first modification consists of decreasing the rate of change of the inlet radius to the monitoring device by implementing a larger funnel. This will allow the transition between the inlet and
the rectangular chamber to be more streamlined. The second and more critical modification will consist of implementing a air flow divider in the centre of the device. The goal is to radially disperse emissions where sensors may be installed, allowing favorable measurement conditions. The electronics (batteries, micro-computer, etc.) would be placed into this core of the device. A CAD design of the new geometry is presented below:

![CAD geometry of the redesign](image.png)

**Fig. 7.** CAD geometry of the redesign, red boundary – inlet, blue boundary - indicating outlet.

The fluid domain is assumed to be occupied using air. The convergence settings of the continuity were set at 0.001 (default settings). The results are presented in figure 8.

![CFD post-processing](image.png)

**Fig. 8.** CFD post-processing of redesigned geometry: 1. Velocity contour plot. 2. Vector velocity plot. 3. Pathline of turbulent intensity.
The figure above presents a color contour plot of the redesigned geometry of the prototype. As can be seen, the flow symmetrically divides around the square shaped core. The inlet velocity is 5.66 m/s. The pressure within the monitoring device is generally between 9 to 11 Pa, which indicates small pressure losses. Furthermore, the simulation showed that the distribution of the air flow shall be symmetric. In figure 8 part 3 the turbulent flow is present in the first third of the monitoring chamber, therefore, it is highly beneficial to place the sensors in regions with high turbulence to decrease pressure losses and provide a statistically representable sample of emission gasses (turbulent flow shall “mix up” the substances uniformly throughout the cross-sectional area). The vector plot indicates a maximum flow speed of 3.4 m/s during the transition phase between the inlet and the sensors. The new design showed a decrease of inlet velocity from 5.8 m/s to 5.6 m/s while leading with more distributed air flow for smart sensors.

5 Conclusion

The article presented the CFD model of the emission monitoring device that measures concentrations of CO, CO2, PM particulates and other organic substances. The model consisted of an inlet, an expansion funnel, a measurement chamber, and a ventilation fan installed at the end.

The model of the initial design showed strong indications of reverse flow within the device. This causes a strong circulation of emission substances which will not allow for accurate measurement of concentrations of pollutants in ambient air. It also showed that the flow is not properly distributed between the sensors and in the measuring device. Additionally, the air flow through the inlet at 12 Pa pressure provided by the fan is 4.59 m/s, which proves the successful requirement of the volume air flow within the device (entire volume of chamber in 5 seconds).

The re-designed geometry of the prototype consisted of two changes, implementation of a larger funnel during transition and placement of a radial flow divider within the monitoring chamber. This allowed to symmetrically distribute the flow, emission particles and static pressures in a circular manner. The CFD model showed a slight decrease of inlet velocity to 5.66 m/s which fulfills the volume flow rate requirements. The vector plot indicated strong vector gradients, which indicate room for optimization of the shape in aims of achieving smooth division of flow within the volume. Additionally, the maximum turbulent intensity take place in the top corners of the separator, which presents an opportunity to trigger air vortices to mix the substances in front of the sensors.

Future design opportunities can be summarized in the following points:

a) Optimization of flow separator in aims of uniform flow distribution.
b) Implement simple vortex generators to induce turbulent flow.
c) Build a 3D printed model and monitor the behavior of dust particles using PIV (Particle Image Velocimetry) method.
Acknowledgment

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