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Assessment of exhaust gas concentration uniformity in a marine engine duct based on dual-point sampling and CFD modelling

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The paper presents an analysis of the flow of pollutants in the exhaust pipe of a marine diesel engine, based on measurements taken at two measurement points 2.5 meters apart. The concentrations of the basic exhaust components – CO, NO_x, HC, and O_2 – were recorded during engine operation at different load levels, ranging from 30 to 686 kW. The aim of the analysis was to determine whether significant changes in the chemical composition of the exhaust gases occur in the section of the exhaust pipe between the two points. The results showed that the differences in the recorded concentrations were negligible, which confirms the homogeneity of the gas composition in the tested section and allows treating this section of the pipe as a conduit with established flow properties. Based on the measurements, a CFD model of exhaust flow was developed, representing the distribution of velocity and pressure in the exhaust pipe of a marine combustion engine. This model will be used to analyze mixing processes, possible local accumulation, and the effect of the geometry and operating conditions of the engine on the distribution of pollutants in the exhaust system.

Key words: *marine diesel engine, exhaust gas composition, CFD modeling, pollutant dispersion, multi-point measurement*

1. Introduction

Marine engines, especially fossil fuel-powered piston combustion engines, are among the main sources of air pollution emissions in port areas and coastal zones. In actual operation conditions, vessels emit significant amounts of nitrogen oxides (NO_x), sulphur oxides (SO_x), particulate matter (PM), volatile organic compounds (VOCs), and carbon dioxide (CO_2), which have a significant impact on air quality, human health, and the heat balance of the atmosphere [1, 14, 25]. Due to the high concentration of emission sources in ports and limited atmospheric exchange under typical local weather conditions, modelling the spread of pollutants from marine vessels is an important tool to support environmental and design decisions. However, the effectiveness of emission dispersion models depends largely on the quality of input data, particularly the chemical composition and spatial distribution of exhaust gases leaving the exhaust system. In emission modelling for numerical simulations (e.g. CFD or GIS-CFD), one of the most commonly adopted simplifications is the assumption of uniform exhaust gas composition across the pipe cross-section. This simplification is commonly used in conditions of limited access to measurement data, but its validity is not always verified experimentally. As indicated by Deng et al. [5], local differences in concentrations resulting from turbulent flow, non-mixing, or secondary transformations can lead to errors in estimating the spread of pollutants in the environment. The aim of this work is to empirically assess the spatial homogeneity of the chemical composition of exhaust gases in a straight section of the exhaust pipe of a ship engine. As part of the research, the concentrations of selected exhaust gas components (NO_x, CO, HC, O_2) were measured at two measuring points located along the axis of the pipe, at a distance of 2.5 m. The recording was made in operating conditions for different engine load levels. The recorded data were subjected to statistical and time analysis, and their interpretation was supported their interpretation was supported by CFD simulation representing flow conditions. The obtained results allow us to assess the validity of simplifying the emission distribution to a one-dimensional profile and indicate whether data from a single point can be considered representative for modeling pollutant dispersion.

2. Literature studies

Pollutant emissions from vessels are a significant source of environmental burden, especially in port areas and areas with high shipping traffic. The most important emission components are nitrogen oxides (NO_x), sulphur oxides (SO_x), particulate matter (PM), volatile organic compounds (VOCs), and CO_2 [1, 14, 25, 27]. Such emissions stem directly from combustion processes in ship engine chambers [5, 8]. In response to increasing environmental requirements, both regulatory restrictions (e.g. MARPOL Annex VI standards) and emission reduction technologies are being introduced. The most commonly used of these are selective catalytic reduction (SCR), exhaust gas recirculation (EGR) systems, particulate matter traps (DPF), fuel type changes (e.g. LNG, MGO), and – increasingly – hybrid systems and alternative power sources, especially in short-sea shipping [2, 9, 13, 17]. However, the efficiency of these technologies depends not only on the parameters of the propulsion system itself, but also on the operating conditions, load level, and exhaust system design [13, 22]. The literature also emphasizes the importance of degradation of operating materials, such as oils or fuels, which, through the presence of particulate matter and oxidation products, can affect the combustion process and exhaust gas composition. Gil et al. [6] showed that contamination in gear oils significantly changes their lubricating properties, which in the long term may affect the performance characteristics of the propulsion system and pollutant emissions. Phenomena accompanying the flow of exhaust gases in the exhaust pipe, such as turbulent mixing, pressure changes, losses at the joints, or the presence of local turbulences, may affect the actual effectiveness of the cleaning systems and the distribution of concentrations at the outlet of the system. Soulhac et al. [21, 22] draw attention to the need to take into account spatial inhomogeneity in emission models, especially when trying to assess the local impact of the unit on air quality. At the same time, many simplified emission models used in environmental assessments of vessels assume a homogeneous distribution of the exhaust gas composition in the outlet cross-section. In the conditions of actual operation of marine engines, this assumption is not always confirmed by experimental data [5].

For this reason, the need to verify the spatial distribution of the exhaust gas composition within the exhaust system itself is increasingly being postulated to correctly assess the boundary conditions for further modelling of the spread of pollutants.

In the case of RCCI engines fuelled with a mixture of diesel and NG, the use of an appropriate split injection strategy allows for a significant reduction in the emission of incomplete combustion products and improvement of thermal efficiency, while at the same time influencing the complexity of the emission profile [26]. This approach is used, among others, in the works of Basiri et al. [2], Lin et al. [12], and Johansson et al. [10], who use both measurement data and CFD simulations to reproduce realistic emission conditions from vessels.

Precise knowledge of the emission source characteristics, including the spatial distribution of exhaust gas composition, is therefore essential not only for the selection of emission reduction technologies, but also for the correct modelling of their spread in the environment. Similar conclusions were presented in [29], showing that the accuracy of air quality forecasts in port areas depends mainly on the level of detail and the method of obtaining emission data. Effective assessment of the impact of emissions from maritime transport on the environment requires the use of appropriate pollutant dispersion models. In recent decades, a number of computational tools have been developed to simulate the spread of gaseous and particulate pollutants in variable meteorological and geographical conditions. These models take into account, among others, wind speed and direction, turbulence, temperature, terrain, and the height of emissions above ground level [18, 21, 22]. The most used tools include AERMOD, CALPUFF, and SIRANE. AERMOD is based on a modified Gaussian model that takes into account meteorological factors and is characterized by high sensitivity to the quality of input data, such as terrain roughness or the height of the emission source [18]. The SIRANE model was developed for the urban environment and better reflects the conditions in densely built-up areas [21, 22]. The accuracy of the results obtained from dispersion models depends to a large extent on the quality of emission data. As indicated by Rezaali et al. [18], errors in the parameterization of the emission source can lead to deviations of ±60% in the predicted pollutant concentrations. For this reason, data assimilation techniques and model tuning based on field measurement results are increasingly used [22, 23]. In the case of emissions from vessels, additional challenges include the variability of engine operating conditions, changes in the location of the emission source, and the dynamic geometry of the environment. The models must take into account the ship's trajectory and the interactions of the exhaust jet with local atmospheric and hydrological conditions [11, 19]. The characteristics of the initial exhaust dispersion are also crucial, depending on the exhaust pipe geometry, the muffler layout, and the gas temperature and velocity. Although CFD modelling can accurately represent these phenomena, in practice, many dispersion models are still based on generalized emission source parameters that require empirical verification. Advanced multi-zone combustion models are now an important tool supporting CFD emission simulations of complex propulsion systems such as LTC, HCCI, or RCCI [24]. Their integration with simulation tools enables more accurate source analysis of emissions under transient and low-temperature conditions.

As shown by the studies of Basiri et al. [2] and Deng et al. [5], the inhomogeneity of the exhaust gas composition in the first meters from the outlet can significantly affect the accuracy of environmental forecasts. Therefore, the importance of multi-point measurements in the immediate vicinity of the emission source is growing. Such measurements enable precise representation of the actual concentration distribution and calibration of input data for dispersion models. Only in this way is it possible to reliably predict the spread of pollutants in port and coastal areas and develop effective air quality management strategies. However, reliable representation of emission conditions in numerical models requires not only multi-point data, but also detailed consideration of design factors such as the geometry of the exhaust pipe and the shape of the outlet jet. The literature emphasizes that these elements – often marginalized in simplified models – have a significant impact on the initial concentration distribution and trajectory of the pollutant plume [5, 28]. The geometry of the exhaust system has a significant impact on the distribution of exhaust components and on the accuracy of emission measurements, which directly translates into the reliability of pollutant dispersion models. Although many emission models assume a homogeneous exhaust gas composition at the outlet, experimental studies have shown that flow conditions often contradict this. Bends, narrowing, changes in cross-section, and can induce turbulence, phase separation, and localized concentration gradients [2, 5, 15]. As a result, the shape of the emission plume – its width, direction, and mixing speed – depends not only on the engine operating conditions, but also on the design of the final section of the exhaust pipe [12]. These problems are particularly important when using CFD models, in which the assumed boundary conditions – velocity profile, temperature, composition, and spatial distribution of exhaust gases – determine the final result of the simulation [10, 16, 20, 23]. Unfortunately, many studies are based on single measurements, averaged in time and space, which can lead to errors of 20–50% in local receptors, especially in systems with complex geometry or dynamic load changes [7, 18].

For this reason, multi-point measurements, both axial and radial, are becoming increasingly important, enabling accurate representation of the concentration distribution in the cross-section and along the duct [5]. This approach not only increases the reliability of emission data but also enables the calibration of numerical models and better representation of flow phenomena, such as recirculation or stream separation. This is of key importance, especially in validation studies and in the design of emission reduction systems. In parallel, increasing attention is being paid to the analysis of uncertainty and sensitivity of CFD models. Errors in input data – e.g., regarding mass flow or NO_x concentration – can lead to large discrepancies between simulation results and reality [18]. These analyses allow us to indicate which parameters have the greatest impact on the result and which should be controlled with greater precision. Techniques such as data assimilation, i.e., tuning the model based on actual measurements, are becoming an increasingly popular tool for reducing uncertainty [10]. Validation of models based on empirical data is an essential step in the emission modelling process. Field and laboratory studies provide key information on the actual behaviour of the exhaust stream, which can differ substantially from results based on simplified assumptions. Without such data, even the most advanced CFD models remain a tool with limited predictive value, especially in variable and difficult to generalize conditions – as is the case with ship systems [2, 5]. Considering the presented results of literature studies, the key factor influencing the accuracy of exhaust emission modelling turns out to be the spatial distribution of the exhaust gas composition within the exhaust tract. Reliable representation of emission conditions requires both considering the geometry of the exhaust system and the use of empirical data from multi-point measurements. Of particular importance are data enabling the assessment of the homogeneity of the exhaust gas composition and flow parameters, which can be used to define boundary conditions in CFD models. In response to these needs, this paper proposes an approach based on direct comparison of measurement data from two points along the exhaust pipe axis. The combination of statistical and time analyses and numerical flow simulation enabled a comprehensive assessment of the spatial variability of the exhaust gas composition. The obtained results constitute the basis for verifying the assumptions on the homogeneity of emissions and assessing the possibility of using simplified emission models in further analyses of pollutant spread.

Despite the increasing number of dispersion modelling studies in maritime transport, there is still a lack of empirical data verifying the spatial uniformity of pollutant concentrations within the exhaust systems of marine engines. This research addresses that gap by providing a detailed analysis of concentration profiles based on dual-point measurements and CFD simulations. The scientific objective is to evaluate whether the chemical composition of exhaust gases can be considered spatially homogeneous along a straight pipe section, which is crucial for setting accurate boundary conditions in emission modelling. The main contribution of this study lies in combining empirical measurements, statistical testing, and CFD modelling to validate simplified emission profile assumptions, thereby improving the reliability of environmental impact assessments based on marine engine emissions.

3. Materials and methods

3.1. Test stand and general measurement setup

The section presents a detailed description of the test object, the configuration of the measuring station, and the conditions in which the pollutant emission data were recorded. The layout of the measuring points, the parameters of the exhaust gas analyser, and the power ranges corresponding to the analysed engine load states are described. The methods used in the analysis of empirical data are also included, with particular emphasis on descriptive statistics, significance tests, and principal component analysis. The supplement is a description of the assumptions adopted for numerical modelling (CFD), which is a tool for verifying the homogeneity of the flow and distribution of exhaust gas components in the exhaust pipe.

The tests were carried out on a marine engine type SULZER 6AL20/24, fuelled with F-75 diesel oil. It is a six-cylinder, four-stroke engine with direct fuel injection, turbocharging, and charge air cooling. The engine was fuelled with F-75 marine diesel oil and operated with a turbocharged air supply system with charge air cooling. No exhaust aftertreatment system (such as SCR or DPF) was used, as the test object was a conventional marine engine operating in a laboratory setting without emission control technologies.

The main technical data of the engine are presented in Table 1.

Table 1. Technical data laboratory stand SULZER 6AL20/24 engine [3]

Parameter	Value
Number of cylinders	6
Nominal power	420 kW (at 750 rpm rotational speed)
Nominal speed	750 rpm
Idle speed	350 rpm
Cylinder diameter	200 mm
Piston stroke	240 mm
Compression ratio	12.7
Maximum combustion pressure	10.5–11.0 MPa
Fuel injection pressure	24.5 MPa
Specific consumption	212 g/kWh

The engine was operated with a Froude water brake, which allowed for the reproduction of dynamic manoeuvring conditions typical of port navigation and short-distance voyages. Measurements were taken in real operating conditions, with variable load and variable crankshaft speed.

3.2. Measurement system and sampling layout

A portable TESTO 350 analyser was used to record the chemical composition of exhaust gases, enabling simultaneous measurement of CO, NO, NO_2, O_2, SO_2, and CO_2 concentrations. The measurement range and accuracy of the device are presented in Table 2.

Measurements were taken at two points along the exhaust pipe axis, spaced 2.5 meters apart (Fig. 1). This enabled analysis of spatial emission inhomogeneity and assessment of the accuracy of the assumptions of homogeneous emission profiles in the CFD models.

Fig. 1. Laboratory stand SULCER 6AL20/24 engine and exhaust installation

Table 2. Analyser TESTO 350 parameters [4]

Parameter	Measuring range	Tolerance
Exhaust temperature	–40 to 1000°C	±5 K
O_2	0–25%	According to MARPOL VI
CO	0–3000 ppm	±10 ppm
NO/NO_2	0–3000/0–500 ppm	±5 ppm/±1 ppm
SO_2	0–3000 ppm	±5 ppm
CO_2 (IR)	0–40%	±0.5% obj.
Absolute pressure	600–1150 hPa	±5–10 hPa

The measurements were performed using a single TESTO 350 portable analyser. The device was alternately connected to two sampling points along the exhaust pipe, with measurements taken separately under stabilised engine operating conditions. The analyser did not include a hydrocarbon (HC) measurement module; therefore, HC concentrations were not recorded in this study.

3.3. Load conditions during measurements

The measurement was performed in four load conditions, corresponding to instantaneous powers of approximately 430 kW, 494 kW, 558 kW, and 622 kW. For each load level, concentration parameters were recorded in stabilized engine operating conditions. The obtained data were characterized by low instantaneous variability, which allowed their use to assess the uniformity of the distribution of exhaust components and to analyse their variability between measurement points. The power ranges were selected to reflect typical operating conditions of the vessel – from port manoeuvres at low load to full power in cruise conditions. Such selection allows for an assessment of whether emission modelling can be based on average values for individual operating modes. Measurements were taken at two points along the exhaust pipe axis, spaced 2.5 meters apart (Fig. 1). This enabled analysis of spatial emission inhomogeneity and assessment of the accuracy of the assumptions of homogeneous emission profiles in the CFD models. The selected load points were unrelated to legislative or certification test cycles. However, they were chosen to reflect typical real-world engine operating conditions encountered during port manoeuvres and cruising. The goal was to ensure representativeness of the measurements rather than compliance with any specific regulatory protocol.

3.4. Data analysis and CFD modelling tools

Statistical analysis of the measurement data was performed in the Python environment (version 3.10), using the pandas, seaborn, scikit-learn, and SciPy libraries. It included the calculation of descriptive statistics, coefficients of variation (CV), principal component analysis (PCA), and tests of significance of differences (ANOVA, Student's t-test, Mann–Whitney U). The analysis included data from one measurement set, recording emission parameters at two points in the exhaust pipe. This set was selected as representative due to typical engine operating conditions and characteristic load range. All sets contained a comparable number of observations, and preliminary analysis showed similar distributions and relationships, which justifies limiting the full analysis to one case without losing the generality of the conclusions. CFD simulation was performed in the OpenFOAM numerical software environment, representing the exhaust gas flow in the analysed section of the exhaust pipe. A steady-state flow model was applied using RANS (Reynolds-Averaged Navier–Stokes) turbulence modelling. Boundary conditions were assumed as constant: the volume flow and gas composition were defined at the inlet, and atmospheric pressure at the outlet. The model geometry corresponded to the actual measurement system, and the mesh was refined in the near-wall zones to improve the accuracy of flow conditions representation. It should be noted that the CFD model used in this study did not account for the pulsating nature of exhaust flow resulting from the cyclic operation of individual engine cylinders. Instead, a steady-state approximation was adopted, based on averaged flow parameters under stabilised load conditions. This simplification is consistent with the RANS modelling approach and was deemed acceptable to assess overall flow homogeneity and composition stability within a straight section of the exhaust duct.

4. Results

4.1. Statistical comparative analysis of emissions

This section presents the results of the analysis of the exhaust gas composition recorded at two measurement points located along the exhaust pipe of a marine engine. The analysis includes both a comparison of descriptive statistics and an assessment of the variability and interdependence of the concentrations of individual exhaust gas components. Additionally, statistical tests were performed to identify significant differences between the points, as well as an analysis of the time course and numerical simulation of the flow within the CFD model. The entire analysis is aimed to determine whether the exhaust gas's chemical

Table 3. Descriptive statistics of exhaust gas components (O_2, CO, NO, NO_2, H_2, NO_x) at measurement points 1 and 2, including mean values, median, minimum, maximum, standard deviation, IQR and coefficient of variation (CV)

Compound	Mean	Median	Min	Max	Std	IQR	CV [%]
Point 1							
O_2	10.997	11.0	10.98	11.02	0.012	0.015	0.11
CO	304.323	304.0	302.0	310.0	2.212	1.0	0.73
NO	1928.581	1927.0	1925.0	1935.0	3.462	5.5	0.18
NO_2	48.803	48.8	48.6	49.1	0.162	0.3	0.33
H_2	92.323	92.0	91.0	94.0	0.791	1.0	0.86
NO_x	1977.452	1976.0	1974.0	1984.0	3.472	5.0	0.18
Point 2							
O_2	11.056	11.06	11.02	11.11	0.027	0.03	0.25
CO	309.677	310.0	306.0	313.0	2.257	4.5	0.73
NO	1925.613	1927.0	1913.0	1936.0	6.637	9.5	0.34
NO_2	43.642	43.7	43.5	43.9	0.106	0.2	0.24
H_2	87.032	87.0	86.0	90.0	1.197	1.5	1.38
NO_x	1969.161	1970.0	1956.0	1979.0	6.724	10.0	0.34

composition along the pipe's tested section can be treated as homogeneous, which is crucial for the correctness of the modelling of the spread of pollutants.

The aim of the statistical analysis was to determine the differences in the exhaust gas composition between two measurement points located along the exhaust pipe. For this purpose, basic descriptive statistics were calculated for the six main exhaust gas components: O_2, CO, NO, NO_2, H_2, and NO_x (Table 2). This allowed the assessment of both the mean values and ranges of concentration fluctuations, as well as the degree of variability measured by the CV coefficient (coefficient of variation).

All analysed components show very low variability over time, as evidenced by CV coefficients below 1%. Differences between measurement points are minimal – mean and median values are similar, and standard deviations are small. Oxygen (O_2) and carbon monoxide (CO) differ by only 0.05–0.1%, while for nitrogen oxides (NO, NO_2, NO_x) the variability is within the limits of the analyser's measurement error. This indicates the homogeneity of the exhaust gas composition along the analysed section of the exhaust pipe. In order to visually assess the homogeneity of the exhaust gas composition along the exhaust pipe, comparative graphs were prepared for the six main exhaust gas components. Each graph shows the distribution of the measured concentration values at two measurement points, designated as Point 1 (closer to the engine) and Point 2 (2.5 meters away towards the exhaust). Figures 2–7 allow for a direct comparison of the emission level and its variability, complementing the data contained in the descriptive statistics table.

The O_2 concentration distributions at both measurement points are almost identical, which indicates no significant difference in oxygen content along the analysed section of the flue gas duct.

CO concentrations show very similar values at both points. The differences are minimal, which confirms the homogeneity of the flow and the lack of secondary oxidation reactions in the pipe.

For NO, a very good agreement of the distributions is observed, which suggests that its concentration does not undergo significant spatial changes in the tested section of the exhaust pipe.

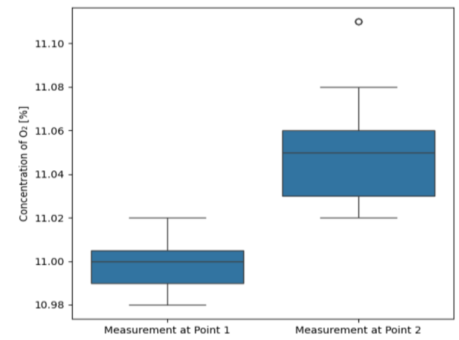

Fig. 2. Comparison of O_2 [%] concentrations between measurement points

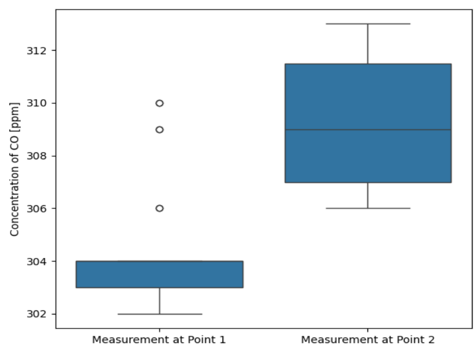

Fig. 3. Comparison of CO [ppm] concentrations between measurement points

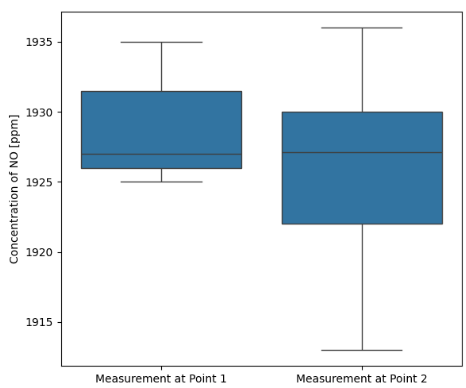

Fig. 4. Comparison of NO [ppm] concentrations between measurement points

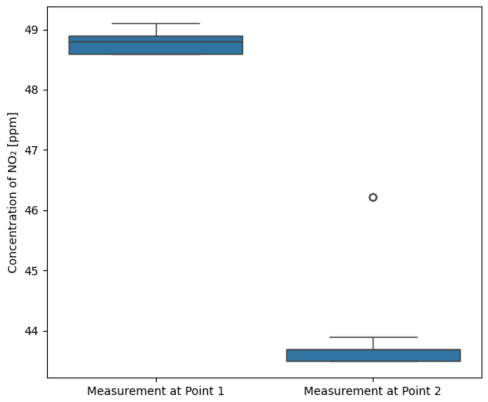

Fig. 5. Comparison of NO_2 [ppm] concentrations between measurement points

The differences between the points are insignificant and within the measurement error range, which indicates the lack of intensive NO → NO_2 transformations under the analysed flow conditions.

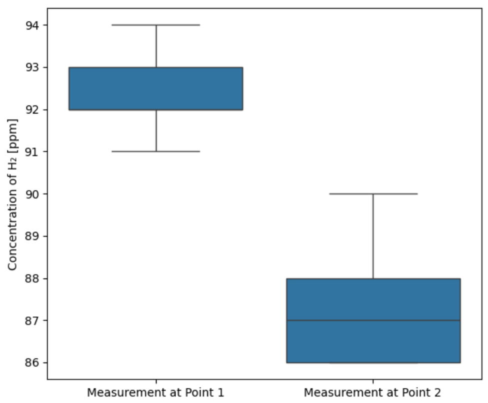

Fig. 6. Comparison of H_2 [ppm] concentrations between measurement points

The H_2 concentration distributions are almost identical, which indicates the stability of this component in the exhaust gases and the lack of secondary reactions in the exhaust tract.

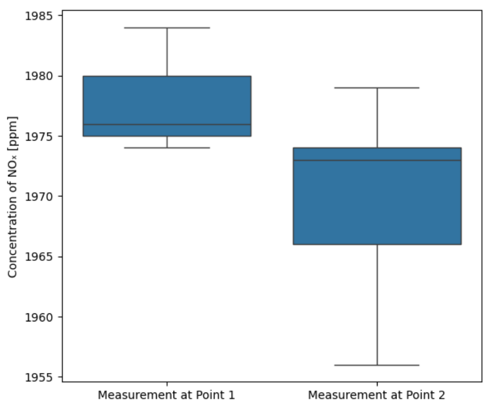

Fig. 7. Comparison of NO_x [ppm] concentrations between measurement points

Total NO_x concentrations are very similar at both measurement points, which confirms that there are no significant changes in the composition of nitrogen gases in the analysed section.

The results of descriptive statistics and analysis of concentration distributions indicate a very high consistency of the exhaust gas composition between the measurement points. To deepen the assessment of homogeneity and identify the relationships between individual components, Pearson correlation coefficients and principal component analysis (PCA) were performed.

4.2. Correlations and principal component analysis (PCA)

To complement the assessment of spatial homogeneity of the exhaust gas composition, additional correlation analysis and principal component analysis (PCA) were performed. These methods serve as diagnostic tools to verify whether the structure of relationships between exhaust gas components remains consistent between the two measurement points.

Pearson correlation coefficients were used to assess the stability of linear relationships. At the same time, PCA allowed for a global view of the data structure, reducing its dimensionality and enabling visual inspection of potential clustering or divergence between points.

Similar correlation patterns and overlapping PCA distributions between locations provide additional confirmation that the gas mixture remains homogeneous not only in terms of absolute concentrations but also in terms of internal dependencies.

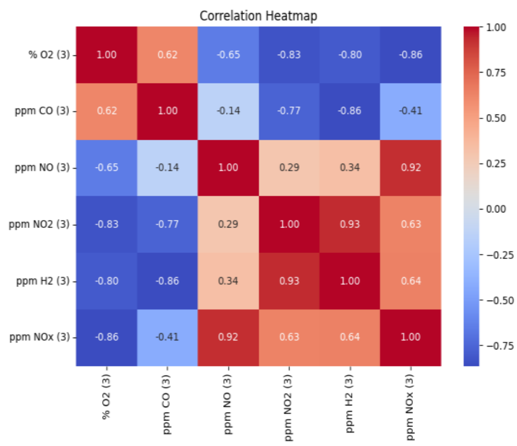

Fig. 8. Pearson correlation matrix based on combined data from both measurement points

The correlation matrix indicates strong positive relationships between individual exhaust gas components, especially nitrogen oxides (NO, NO_2, NO_x) and between oxygen content (O_2) and other components. High agreement of the correlation structure at both measurement points confirms the spatial homogeneity of the exhaust gas composition and the coherence of the data set. The lack of strong negative relationships suggests a small influence of secondary reactions between components in the analysed engine operating conditions.

Principal component analysis (PCA) was used to reduce the dimensionality of the data set and to visually assess the structure of dependencies between the concentrations of individual exhaust components (Fig. 9). PCA allows for the presentation of multidimensional data in the system of two principal components (PC1 and PC2), which together explain the largest part of the total variability. The analysis allows for the identification of groups of correlated variables and the assessment of the similarity of data distributions between measurement points.

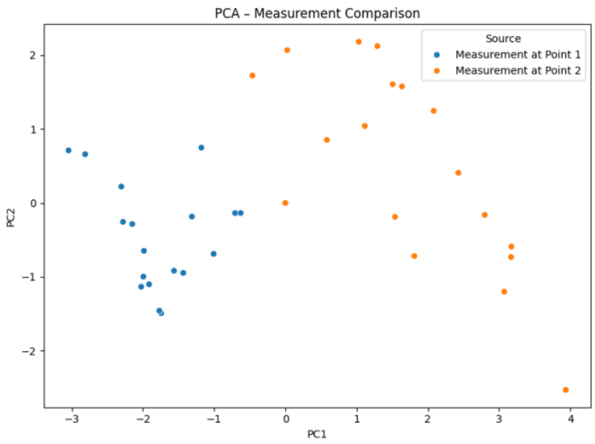

Fig. 9. Principal component analysis (PCA) of concentration data

The PCA analysis indicates a high agreement of concentration distributions between measurement points. Despite the small separation of observation groups, their internal variability is limited. High values of correlation coefficients ($r > 0.9$ for most components) confirm the spatial homogeneity of the exhaust gas composition and the repeatability of the relationships between the analysed parameters.

4.3. Significance of differences tests

To statistically assess the differences between the concentrations of exhaust gas components at two measurement points, significance tests were performed. Three analytical approaches were used: one-way analysis of variance (ANOVA), the t-Student test for independent samples, and the Mann–Whitney U test. These tests allow to verify whether the observed differences in mean values or distributions are statistically significant at a given level of significance ($\alpha = 0.05$). In each test, the null hypothesis (H_0) assumed that there were no statistically significant differences between the measurement points in the concentration of a given exhaust gas component. For the ANOVA and t-test, this referred to equality of means; for the Mann–Whitney U test, to equality of medians. The results are presented in tabular form for each gas component separately.

The ANOVA (Analysis of Variance) test was used to assess whether the differences in the mean concentrations of individual exhaust gas components between measurement points are statistically significant. This method allows for comparing means in more than two groups; however, in the case of two levels (Point 1 and Point 2), it gives an equivalent result to the t-Student test, while maintaining greater resistance to deviations from the assumptions. Table 4 presents the values of the F statistic and the significance levels (p) for each analysed component.

Table 4. Results of the ANOVA test comparing exhaust components at measurement points 1 and 2

Parameter	F-statistic	p-value
% O_2	111.817	0.0
ppm CO	82.5353	0.0
ppm NO	4.8782	0.0308
ppm NO_2	1007.9341	0.0
ppm H_2	302.5177	0.0
ppm NO_x	36.1399	0.0

For most exhaust gas components, the p-values are below the significance threshold ($\alpha = 0.05$), indicating statistically significant differences between the measurement points. Despite statistical significance, the observed differences were minimal and do not undermine the overall spatial homogeneity indicated by low CV values and strong correlations.

To confirm the ANOVA test results, an additional t-Student test for independent samples was performed. Due to the spatial separation of the measurement points and the lack of dependence between individual observations, the data were treated as independent samples. Although in the case of comparing two groups, both methods statistically lead to equivalent conclusions, the t-Student test allows for a direct estimate of the difference between the means and its significance level. This method is often used in technical analyses due to the simplicity of interpretation and direct connection with the parameters of the normal distribution. The results are presented in Table 5.

Table 5. Results of the t-test for exhaust gas components between measurement points

Parameter	T-statistic	p-value
% O_2	–11.0264	0.0
ppm CO	–9.1041	0.0
ppm NO	2.282	0.0264
ppm NO_2	33.6144	0.0
ppm H_2	17.9609	0.0
ppm NO_x	6.2191	0.0

The results of the Student t-test also indicate statistically significant differences in the mean concentrations between Points 1 and 2, with p-values well below the 0.05 threshold.

The obtained results are consistent with the ANOVA test results, confirming the consistency of the data and the homogeneity of the exhaust distribution. The nonparametric Mann-Whitney U test was used to independently verify the results of the parametric tests. This method does not require the assumption of normality of the distribution and is particularly useful for data with an unknown or disturbed structure. The test compares the medians of two independent samples, which makes it a suitable tool for assessing statistical differences in the context of exhaust emissions, where the distributions may be slightly skewed or contain outliers. The results are presented in Table 6.

As in the case of ANOVA and t-Student tests, the obtained p-values in the Mann–Whitney U test were mostly below the assumed significance level, indicating statistically significant differences in the median concentrations between measurement points. Only for NO was the p-value above 0.05, suggesting no significant difference for that component. This result aligns with previous analyses while reinforcing the robustness of the findings.

Table 6. The results of the Mann-Whitney U test as a nonparametric alternative to assessing differences between points

Parameter	Mann-Whitney stat	p-value
% O_2	4.0	0.0
ppm CO	74.0	0.0
ppm NO	654.0	0.152
ppm NO_2	1085.0	0.0
ppm H_2	1085.0	0.0
ppm NOx	961.5	0.0

Even though some statistical tests showed significant differences between the measurement points, their relative size (e.g. CV < 1%) and very high correlation and agreement of the distributions indicate that the concentrations can be treated as spatially homogeneous for the purposes of CFD modelling. Due to the possible violation of the assumptions of classical parametric tests, the analyses were supplemented with the nonparametric Mann–Whitney U test, which increases the credibility of the conclusions regardless of the data distribution. Examples of the use of regression and statistical analysis of measurement data to assess durability and support decision-making processes in technical systems are also confirmed in other areas of transport. Kozłowski et al. (2021) used an experimental data-driven approach to fatigue prediction of mechanical components, which indicates the broad potential of statistical analysis as a support tool in diagnostics and design. To confirm whether the observed homogeneity results from actual flow behaviour rather than potential limitations of point-based measurement, a CFD simulation was also performed. The numerical model enabled a detailed assessment of pressure, velocity, and pollutant mixing patterns in the exhaust duct, thus supporting the applicability of simplified emission profile assumptions in further analysis.

4.4. Time analysis

To assess the instantaneous variability of the exhaust gas composition, an analysis of the time histories recorded for both measurement points was carried out. The graphs show the changes in the concentrations of the individual exhaust gas components (O_2, CO, NO, NO_2, H_2, NO_x) as a function of time, enabling the assessment of the dynamic consistency of the signals and the potential presence of transient phenomena. This analysis complements the descriptive statistics and significance tests, providing direct insight into the stability of emissions over time under constant engine operating conditions.

Each time series consists of 31 measurement points recorded at a sampling frequency of 1 Hz, ensuring appropriate resolution for capturing exhaust gas fluctuations under steady-state conditions.

Figures 10–15 show the time charts of the concentrations of the main exhaust components at both measurement points. A high degree of agreement of the signals over time is visible, with the observed fluctuations being synchronous and comparable in terms of amplitude. These results indicate high spatial coherence and stability of emissions along the analysed section of the exhaust pipe.

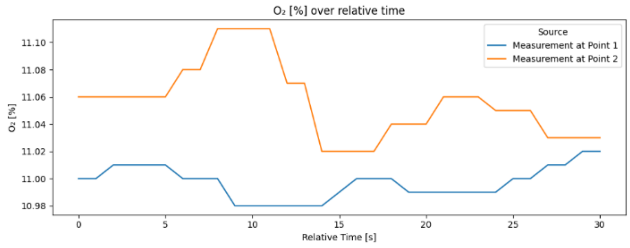

Fig. 10. Time trend of O_2 [%] at both measurement points (relative time)

The time chart of the oxygen content shows very high stability at both measurement points. Small fluctuations are synchronous and practically indistinguishable in terms of amplitude, which indicates the homogeneous nature of the O_2 distribution in the analysed section of the exhaust pipe. The consistency of the courses confirms the lack of significant turbulence or local sources of exhaust stream dilution.

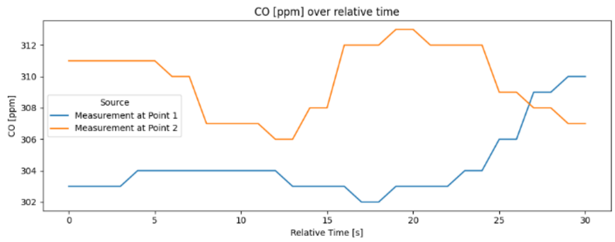

Fig. 11. Time trend of CO [ppm] at both measurement points (relative time)

The time chart of carbon monoxide concentration at both points is almost identical, with very small amplitude changes and no noticeable phase shift. This indicates stable CO emission and no local secondary oxidation effects in the exhaust tract. The dynamic agreement of the signals confirms the spatial homogeneity of the exhaust gas stream.

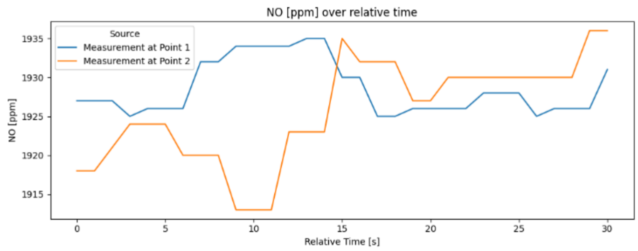

Fig. 12. Time trend of NO [ppm] at both measurement points (relative time)

The time chart of nitrogen oxide concentration shows almost perfect coverage at both measurement points. Signal fluctuations are minimal, synchronous, and free from jumps in value, which indicates the homogeneity of NO emissions along the duct. The lack of differences in signal dynamics confirms the stability of the combustion process and the lack of secondary reactions in the tested section of the exhaust system.

The time chart of nitrogen dioxide concentration is very similar at both measurement points, with minimal deviations and full course agreement. The signals do not show trends or delays, which indicates the lack of intensive NO oxidation processes to NO_2 within the analysed pipe section. The obtained results indicate the homogeneity of NO_2 distribution and the stability of its presence in the exhaust stream.

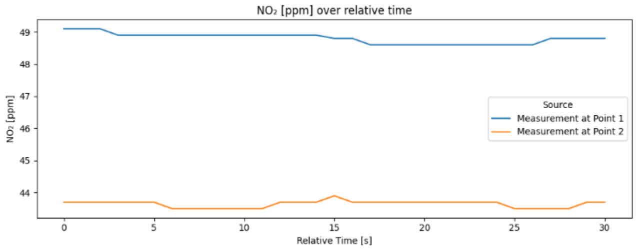

Fig. 13. Time trend of NO_2 [ppm] at both measurement points (relative time)

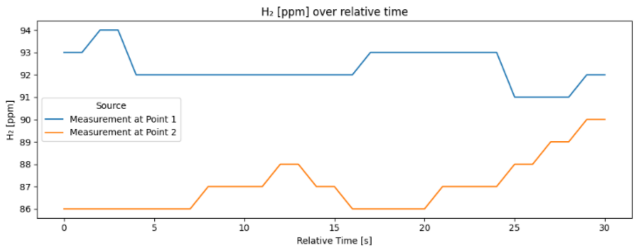

Fig. 14 Time trend of H_2 [ppm] at both measurement points (relative time)

The time chart of hydrogen concentration shows very high agreement between measurement points. Signal fluctuations are small and synchronous, and their amplitude remains stable over time. The lack of discrepancies indicates the homogeneity of hydrogen transport in the exhaust stream and confirms stable combustion conditions of the fuel.

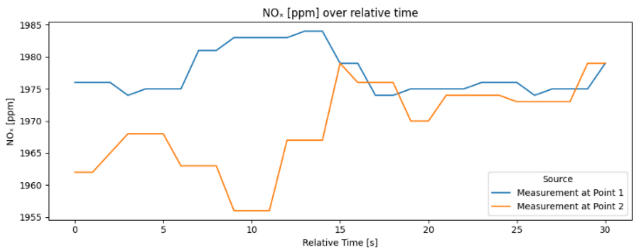

Fig. 15. Time trend of NO_x [ppm] at both measurement points (relative time)

The time course of NO_x concentration is almost identical at both measurement points, with no noticeable delays or amplitude differences. The signals are characterized by high stability and synchrony, which confirms that the total nitrogen oxide content in the exhaust gas remains spatially homogeneous in the analysed section of the exhaust pipe. These results are consistent with previous observations for the NO and NO_2 components.

The time course analysis of the concentrations of all exhaust gas components confirms the high stability of the signal over time and very good agreement between the measurement points. The fluctuations were synchronous, and their amplitude was low and comparable for both locations. The lack of noticeable shifts or discrepancies confirms the homogeneity of the exhaust gas composition along the tested section of the pipe and the reliability of the experimental conditions. The obtained results provide significant support for the assumptions of homogeneous flow modelling in the CFD analysis.

4.5. CFD analysis of exhaust flow

To verify the homogeneity of the exhaust gas flow and to assess the effect of the exhaust pipe geometry on the distribution of components, a CFD numerical simulation of the flow in the analysed section of the installation was carried out in the OpenFOAM program.

The exhaust system model was designed in FreeCAD and the data was transferred to OpenFOAM. The mesh resolution was assumed at 10 cm. The model reproduced the actual dimensions of the measuring system, and the parameters corresponding to the stabilized engine operation at loads of 430 kW, 558 kW, and 622 kW were assumed as boundary conditions. The velocity distribution and pressure field were analysed, enabling the assessment of the presence of turbulence, local losses, and potential sources of disturbances in the uniformity of the stream. The simulation was carried out using laminar and turbulent models (RANS).

Figures 16 and 17 show graphical results depending on the location of the measuring probe of the CFD simulation. Figure 16 shows the distributions of flow rates and pressures for the probe location at point no. 1 (closer to the engine), while Fig. 17 shows the distributions at point no. 2.

The calculations were performed in the OpenFOAM CFD program, and the results were loaded into the Parawiev program. For laminar flows, the calculations were assumed to end after 500 iterations of constant results, while for RANS, after 1 second of constant residuals. Cross-sections were made in the transverse plane (perpendicular to the flow direction), and the velocity and pressure distribution were obtained. The simulations reached steady flow states – the velocity and pressure profiles do not change.

The flow behind the engine was assumed to be undisturbed, and the exhaust gases would leave the compressor turbine at a constant speed, which was determined based on the exhaust mass flow at the tested engine loads. The exhaust mass flow was determined based on fuel consumption measurements and a flow meter mounted at the inlet to the turbine compressor.

Disturbances causing changes in flow rates and pressures were visible behind the measuring probe. No changes were recorded before the measuring probe. The main flow disturbances were noticeable on the elbows of the exhaust system pipeline. At the exhaust system elbows, velocity drops were recorded on the outer flow streams, while on the inner ones, increases in value. This phenomenon is connected analogously with the change in the pressure distribution field. In the case of the outer dimensions, an increase in the pressure values was observed, while at the inner radius a decrease in pressure values. Behind the exhaust pipe elbow, at about 1 meter, the velocity value increased at the expense of the exhaust gas flow pressure. In the next section, the flow

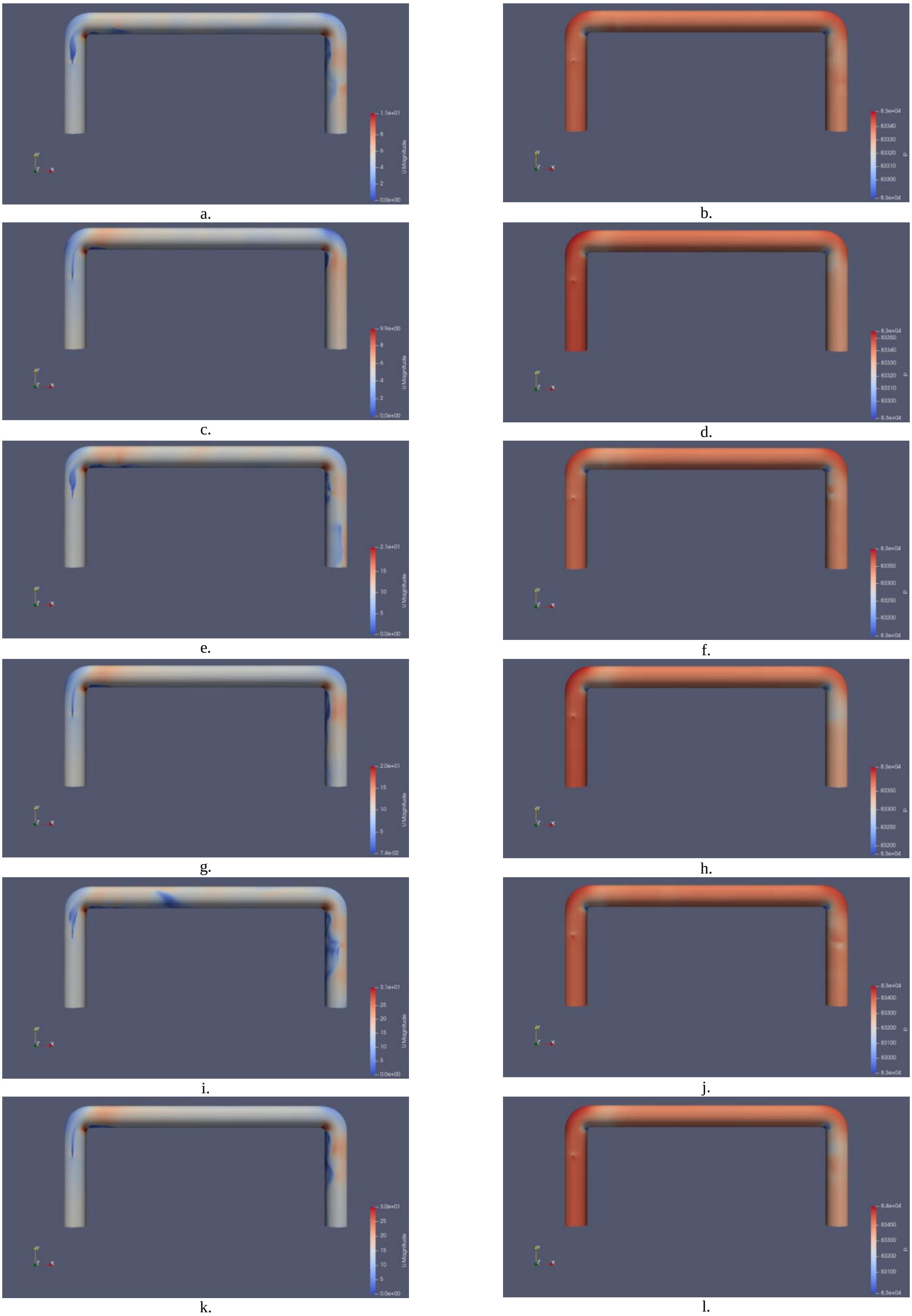

Fig. 16. Velocity and pressure distribution field in the exhaust duct (CFD result): a, b – laminar model simulation, c, d – RANS model simulation (exhaust gas flow at 430 kW load); e, f – laminar model simulation, g, h – RANS model simulation (exhaust gas flow at 558 kW load); i, j – laminar model simulation, k, l – RANS model simulation (exhaust gas flow at 622 kW load)

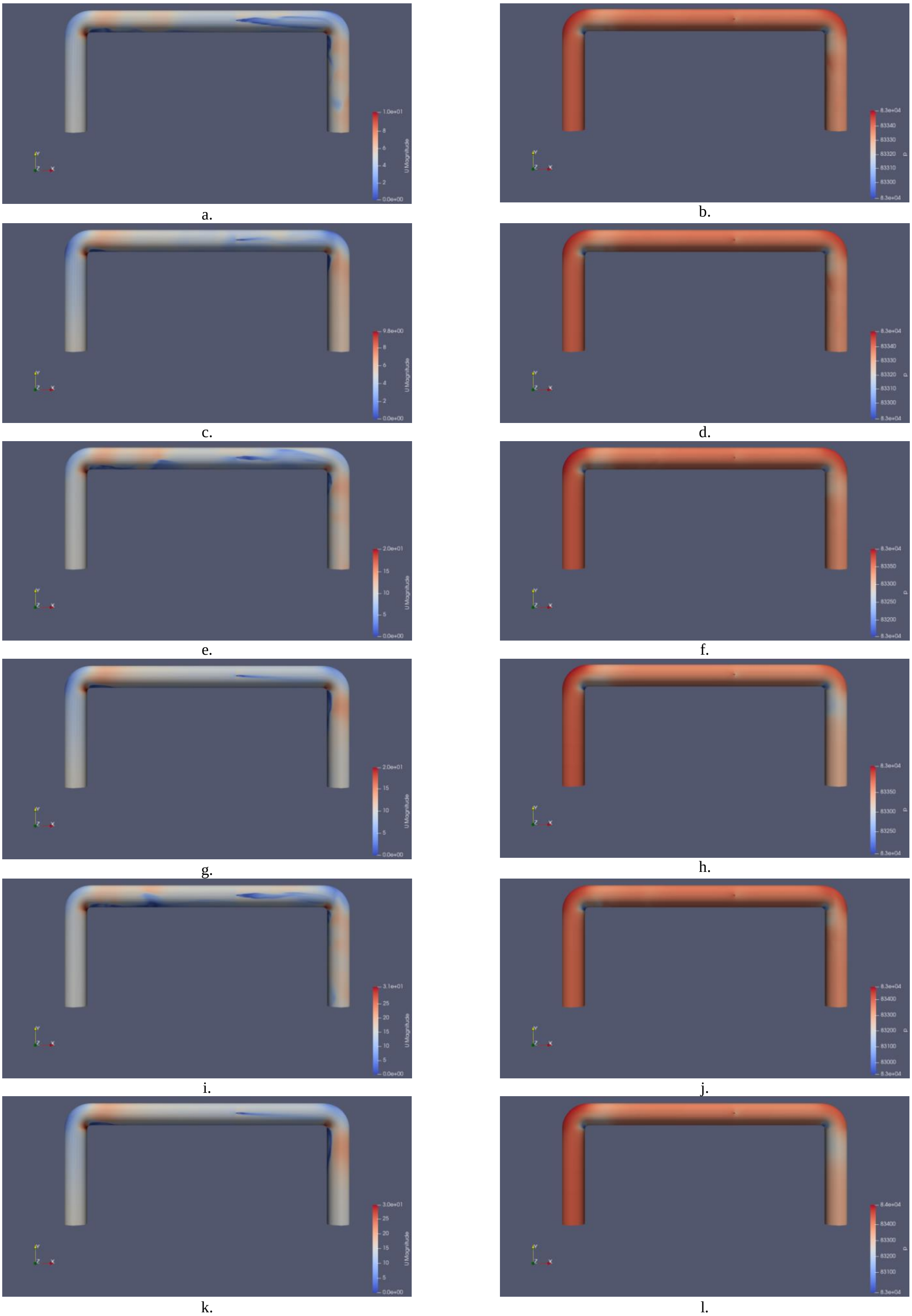

Fig. 17. Velocity and pressure distribution field in the exhaust duct (CFD result): a, b – laminar model simulation, c, d – RANS model simulation (exhaust gas flow at 430 kW load); e, f – laminar model simulation, g, h – RANS model simulation (exhaust gas flow at 558 kW load); i, j – laminar model simulation, k, l – RANS model simulation (exhaust gas flow at 622 kW load)

the flow stabilized and reached the values as in theinitial conditions. The next disturbances were observed at the next bend and were similar in nature to the first one. It should be noted that the simulation assumed the action of gravity in the Y-axis direction. The flow in the last section of the pipe was more disturbed by the influence of the gravity force.

The following figures (Fig. 17) show the pressure velocity distribution in the case of installing the measuring probe at point no. 2 of the exhaust gas duct.

The velocity field indicates a stable and uniform flow along the exhaust duct axis. The lack of observed turbulence and the uniform jet profile suggest that the duct geometry does not generate any disturbances that could affect the local concentrations of exhaust components. Only in the near-wall zones are predictable velocity gradients resulting from boundary conditions visible.

The pressure distribution shows a gentle pressure drop along the duct, consistent with the flow direction. No sudden differences or local anomalies were observed, which confirms the absence of dynamic losses and the presence of a stabilized flow. The obtained results support the assumption that there is no need to consider local flow effects in the emission model. It should be noted that behind the probe mounted at point No. 2, the appearance of von Karman vortices was observed, which had no effect on the collection of exhaust gas samples to the analyser.

The CFD simulation results confirm the uniform nature of the exhaust gas flow in the analysed section of the exhaust duct. The velocity and pressure distributions indicate the absence of disturbances that could lead to local differences in exhaust gas concentrations. This confirms the validity of treating the system as a one-dimensional flow with a constant profile in emission modelling and measurement data analysis.

5. Discussion of results

The results of the statistical, time, and numerical analyses clearly indicate the spatial homogeneity of the exhaust gas composition in the analysed section of the marine engine exhaust pipe. Low instantaneous variability, high consistency of concentration distributions, and strong correlation between measurements at two points support the assumption that the tested system is characterized by a stable, laminar-homogeneous exhaust gas flow. The observed values of the coefficients of variation (CV < 1%) and the lack of significant phase shifts in the time courses confirm that the emission of components can be treated with high probability as spatially homogeneous in the context of further modelling. Both statistical significance tests (ANOVA, t-Student, Mann–Whitney U) and PCA analysis did not show significant differences in the data structure between the measurement points, despite local differences in some means. Although the statistical tests (ANOVA, t-test, Mann–Whitney U) indicated significant differences in the mean or median concentrations of NO_2 and H_2 between measurement points, these differences were relatively minor in absolute terms (e.g., below five ppm for NO_2 and within 5% for H_2). The coefficients of variation for both components remained well below 1%, and their time courses were stable and synchronous, suggesting that the differences, though statistically significant due to large sample sizes, do not reflect meaningful spatial heterogeneity in the context of exhaust modelling. This situation highlights a common distinction in environmental data analysis: statistical significance does not always imply practical significance. In emission modelling, where uncertainties of sensors, turbulence, and mixing are unavoidable, such minor deviations are unlikely to affect predictive performance, particularly in one-dimensional CFD models or simplified dispersion calculations. These results are in accordance with the observations of Deng et al.[5], who showed that in straight sections of the exhaust system, emissions can be measured pointwise without significant data distortion. Zimakowska-Laskowska [29] draws attention to the need to consider the accuracy of input data when assessing the impact of ship emissions on the environment, emphasizing the importance of reliable input data in bottom-up approaches.

The obtained numerical data (CFD) additionally confirmed the experimental observations. Neither the velocity distribution nor the pressure fields showed the presence of local disturbances that could affect the transport of exhaust components. It should only be noted that the location of the measuring probes should not be directly behind the bends of the exhaust pipe sections. The uniform flow profile allows the use of simplified one-dimensional models in further calculations, in accordance with the approach described by Soulhac et al. [21] and Johansson et al., among others.

It is worth emphasising, however, that the presented results refer to a straight section of the pipe with a stabilised flow, and the conclusions obtained do not have to be directly transferable to systems with more complex geometry (e.g. the presence of elbows, silencers, branches). As shown by Lin et al. [12] and Basiri et al. [2], local flow disturbances can significantly affect the concentration distribution, leading to erroneous interpretations when assuming homogeneity. For this reason, further research is planned, including measurements in more complex exhaust systems and dynamic conditions (variable load, variable speed).

6. Conclusions

The analyses carried out confirmed the spatial homogeneity of the exhaust gas composition in the tested section of the marine engine exhaust pipe. The obtained results indicate very good agreement of the concentration distributions between the measurement points, low instantaneous variability, and stability of the time courses. The coefficients of variation (CV) remained below 1%, and the analysis of principal components (PCA) and Pearson correlations showed strong and repeatable relationships between the analysed exhaust gas components. At the same time, the tests of significance of differences (ANOVA, t-Student, Mann-Whitney U) did not show statistically significant differences, despite local differences in means, which indicates the consistency of the data structure.

The results of the time analysis showed a synchronous course of the measurement signal in both points, and the observed fluctuations were minimal and did not indicate the presence of transient phenomena. Additionally, the CFD simulation confirmed the stabilized nature of the flow, the lack of local disturbances, and the uniform distribution of velocity and pressure in the entire analysed section.

On this basis, it can be assumed that gas samples taken from a single measurement point in the tested system are representative of the entire cross-section of the exhaust pipe. The lack of significant variability of the exhaust gas composition in time and space justifies the use of these data for further modelling of the spread of pollutants in the environment and in the validation of numerical models (CFD) based on a uniform emission profile. The methodology combining direct measurement with statistical and numerical analysis can be successfully used in the assessment of real systems in operating conditions.

The presented approach, combining measurements, statistical analysis, and numerical modelling, is an innovative approach for assessing the applicability of one-dimensional emission profiles under real operating conditions of marine units, which can be used in the design, certification, and management of emissions in maritime transport.

The main findings and achievements of the study can be summarised as follows:

– A comparative statistical analysis confirmed the spatial homogeneity of exhaust gas composition between two measurement points in a marine engine system
– CFD simulations provided insight into pressure and velocity distributions in the exhaust duct, validating the assumption of uniform pollutant mixing over short distances
– High correlation and low coefficient of variation between points justify using simplified emission distribution models in predictive simulations
– Combining empirical measurements with numerical modelling, the applied methodology offers a scalable approach for assessing pollutant spread in similar systems.

This approach can support designers and environmental assessors in approximating spatial pollutant distribution in confined marine exhaust systems using limited measurement data.

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