Dinamika Teknik Mesin 16(1) (2026) 76-84

Dinamika Teknik Mesin
Jurnal Keilmuan dan Terapan Teknik Mesin
http://dinamika.unram.ac.id/index.php/DTM/index

Numerical study of exhaust flow behavior in a calcium carbide waste adsorber for two-wheel vehicle applications

H.S. Tira*, Y.A. Padang, N. Kaliwantoro, A.D. Catur, IG.N.K. Yudhyadi, S. Rahman
[1]Mechanical Engineering Department, Engineering Faculty, the University of Mataram, Jl. Majapahit no. 62, Mataram, NTB, 83125, Indonesia. HP. 087878580219
*E-mail: hendrytira@unram.ac.id

ARTICLE INFO

Article History:
Received 26-12-2025
Accepted 30-03-2026
Available online 01-04-2026

Keywords:
Calcium carbide
Exhaust emission,
Computational fluid dynamics
Turbulence kinetic energy

ABSTRACT

Calcium carbide waste has demonstrated potential as an adsorber material for motorcycle exhaust emission control; however, the internal flow and thermal mechanisms governing its performance remain unclear. This study presents a computational fluid dynamics (CFD) analysis of exhaust gas flow through a calcium carbide waste adsorber to elucidate pressure, velocity, temperature, and turbulence characteristics. Simulations were conducted for adsorber lengths of 50, 100, and 150 mm, with the 150 mm configuration selected as a representative case due to similar overall trends. The results indicate a gradual pressure reduction along the exhaust system, flow acceleration within the adsorber due to cross-sectional constriction, and non-uniform temperature distribution influenced by asymmetric flow patterns. Turbulence kinetic energy increases upon gas entry into the adsorber and varies with adsorber length, highlighting the role of geometry in flow mixing and turbulence dissipation. These findings provide physical insight into the mechanisms underlying the emission reduction observed in previous experimental studies.

Dinamika Teknik Mesin, Vol. 16, No. 1, April 2026, ***p. ISSN: 2088-088X, e. ISSN:*** **2502-1729**

1. INTRODUCTION

Two-wheel vehicles are among the most widely used transportation modes in urban areas, particularly in developing countries, due to their affordability and mobility. However, the rapid increase in the number of motorcycles has led to a significant contribution to urban air pollution, primarily through exhaust emissions such as hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NOx) (Tira et al., 2024; Tira, et al., 2023). Compared to four-wheel vehicles, the emission control systems of motorcycles are generally simpler and less effective, making after-treatment solutions for two-wheel vehicles an important research topic (Tira and Ikhsan, 2023).

Conventional exhaust after-treatment systems rely heavily on catalytic converters that utilize precious metals such as platinum, palladium, and rhodium. While these materials provide high catalytic activity, their high cost significantly increases vehicle production costs and limits their application, especially in low-cost vehicles (Eliopoulos et al., 2022). Moreover, the reliance on scarce and non-renewable precious metals raises sustainability concerns. As a result, there is a growing demand for alternative emission control materials that are

https://doi.org/10.29303/dtm.v16i1.1247

cost-effective, environmentally friendly, and derived from abundant or waste resources (Patel et al., 2022). One promising approach is the utilization of industrial or household waste materials as adsorbents, which not only reduces emission levels but also contributes to waste minimization and circular economy principles. Calcium carbide waste, generated as a by-product of acetylene gas production and welding processes, is one such material that has attracted attention due to its high calcium-based content and adsorption potential (Karim et al., 2023).

Previous experimental studies have demonstrated that calcium carbide waste can function as an effective adsorbent for reducing exhaust emissions from two-wheel vehicles (Tira and Wirawan, 2023). These studies reported a noticeable decrease in HC, CO, and CO_2 emissions when the exhaust gas passed through a calcium carbide waste adsorber. Nevertheless, experimental investigations are inherently limited to measurable macroscopic parameters, such as emission concentrations, temperature at discrete points, and overall pressure drop. The internal flow behavior within the adsorber such as velocity distribution, turbulence development, detailed pressure variation, and temperature contours before, inside, and after the adsorber cannot be directly observed through laboratory testing alone. This limitation restricts the understanding of the fundamental mechanisms governing gas–solid interaction and adsorption effectiveness.

To overcome these limitations, computational fluid dynamics (CFD) provides a powerful numerical tool to visualize and analyze internal exhaust gas flow behavior in detail. Through CFD simulation, important variables such as flow pattern, velocity streamline, pressure distribution, temperature field, and turbulence kinetic energy can be evaluated simultaneously (Sylvia et al., 2019; Wakid et al., 2024). Understanding these variables is essential for improving adsorber performance, as they directly influence gas residence time, mixing intensity, heat transfer, and contact efficiency between exhaust gases and the adsorbent surface. By identifying flow acceleration, recirculation zones, and turbulence characteristics inside the adsorber, numerical analysis enables researchers to refine and redesign not only the adsorber geometry itself but also the upstream exhaust channel configuration to enhance adsorption effectiveness and overall emission reduction performance.

Therefore, the present study conducts a numerical investigation of exhaust gas flow behavior in a calcium carbide waste adsorber using CFD. The simulation aims to provide mechanistic insights into pressure, velocity, temperature, and turbulence characteristics that support previously reported experimental findings without reproducing emission measurements. In addition to improving the current adsorber design, the knowledge gained from this study is expected to be transferable to other combustion-related applications, such as household combustion systems, industrial furnaces, power generation units, and waste incinerators, where cost-effective and sustainable emission control solutions are required (Martias et al., 2025; Soemardi et al., 2010). By combining waste-based materials with numerical flow analysis, this research contributes to the development of affordable, sustainable, and adaptable exhaust emission mitigation strategies.

2. RESEARCH METHODS

2.1. Numerical model and geometry configuration

The present study employs a computational fluid dynamics (CFD) approach to investigate the exhaust gas flow behavior in a calcium carbide waste adsorber applied to a two-wheel vehicle exhaust system. The numerical analysis was conducted to provide a detailed understanding of internal flow, thermal, and turbulence characteristics that cannot be directly observed in laboratory emission testing. Rather than reproducing experimental measurements, this numerical study focuses on elucidating the physical mechanisms governing gas–solid interaction within the adsorber.

The computational geometry was developed based on the modified exhaust system and adsorber configuration used in the previous experimental investigation. The model consists of an exhaust pipe integrated with a cylindrical calcium carbide waste adsorber installed downstream of the exhaust manifold. The adsorber has an outer diameter of 88 mm and contains 19 internal channels with a diameter of 6 mm each, arranged to allow exhaust gas to pass through the adsorbent material. To examine the influence of adsorber length on flow behavior, three adsorber configurations were considered, with lengths of 50, 100, and 150 mm. The geometric details of the adsorber and the modified exhaust system are illustrated in Figures 1 and 2, respectively.

https://doi.org/10.29303/dtm.v16i1.1247

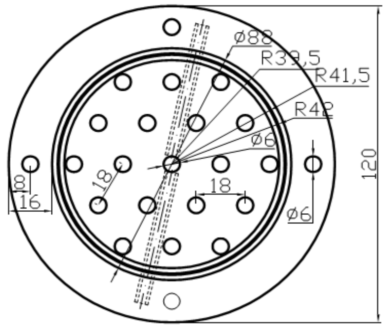


Figure 1. Front view and dimensional details of the calcium carbide waste adsorber

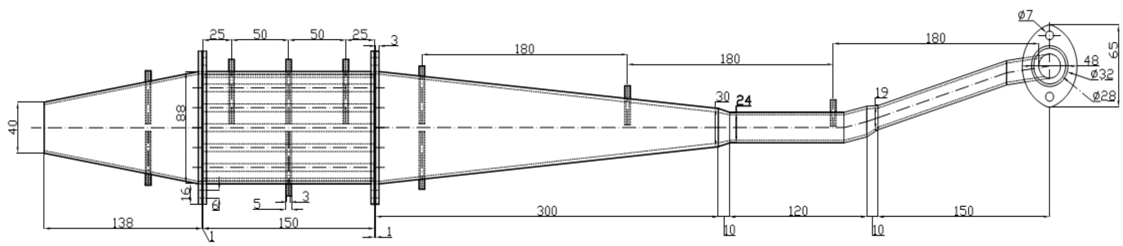


Figure 2. Schematic of the modified exhaust system with integrated calcium carbide waste adsorber

All numerical models were constructed to represent the internal fluid domain of the exhaust system, while the solid adsorbent material was treated implicitly through its geometric constraints on the flow. This modeling approach enables a focused analysis of pressure distribution, velocity development, temperature variation, and turbulence kinetic energy within the exhaust system, providing mechanistic insights that complement previously reported experimental emission reduction results.

2.2. Governing equations, mesh, and boundary conditions

The numerical simulations were carried out using ANSYS Fluent by solving the steady-state, three-dimensional governing equations of fluid flow and heat transfer. The exhaust gas flow inside the modified exhaust system was modeled using the conservation equations of mass, momentum, and energy. Turbulence effects were accounted for through a Reynolds-averaged Navier–Stokes (RANS) approach, which is commonly adopted for internal exhaust flow simulations due to its balance between accuracy and computational efficiency.

The computational domain consisted of the internal fluid region of the exhaust pipe and the adsorber channels. A three-dimensional mesh was generated with local refinement applied in critical regions, including exhaust bends, the conical transition section, and the adsorber channels, to accurately capture velocity gradients and turbulence development. The exhaust gas entered the domain through the inlet boundary defined by representative flow and temperature conditions, while a pressure outlet boundary was applied at the downstream end of the exhaust system. All solid walls were treated with a no-slip condition, and thermal boundary conditions were enabled to account for heat transfer between the exhaust gas and the exhaust wall. The simulations were iterated until convergence was achieved for all residuals and key flow variables. To improve clarity and reproducibility, the main numerical settings applied in this study are summarized in table 1.

Table 1. Numerical simulation parameters.

Parameter	Description
Software	ANSYS Fluent
Solver type	Pressure-based, steady-state
Flow model	Three-dimensional internal flow
Turbulence model	RANS (realizable k–ε)
Energy equation	Enabled
Inlet boundary	Velocity / mass flow inlet with prescribed temperature
Outlet boundary	Pressure outlet
Wall condition	No-slip
Discretization scheme	Second-order upwind

Convergence criteria	Residuals $\leq 10^{-5}$

2.3. Simulation cases and data analysis

The numerical simulations were conducted for three different adsorber lengths, namely 50, 100, and 150 mm, to investigate the influence of geometric variation on exhaust gas flow behavior. Preliminary comparisons indicated that the overall trends of pressure, velocity, and temperature distributions were similar across all configurations. Therefore, the 150 mm adsorber was selected as a representative case for detailed discussion of flow and thermal characteristics.

The numerical results were analyzed in terms of pressure distribution, velocity streamline, temperature field, and turbulence kinetic energy. A comparative analysis among the three adsorber lengths was performed specifically based on turbulence kinetic energy to highlight the effect of adsorber length on flow mixing and turbulence dissipation. The post-processing of simulation data was carried out using contour plots and streamline visualization to facilitate qualitative and mechanistic interpretation of the exhaust gas flow behavior within the adsorber.

3. RESULTS AND DISCUSSION

3.1. Temperature distribution

The temperature contour for the 150 mm adsorber configuration is presented as a representative case, since preliminary simulations indicated that similar temperature distribution trends were observed for the shorter adsorber lengths. As shown in the figure 3, a high-temperature region is clearly observed near the exhaust inlet, immediately downstream of the exhaust manifold. The exhaust gas temperature gradually decreases along the flow direction as the distance from the exhaust manifold increases. This temperature decay is associated with heat transfer to the exhaust wall and the surrounding environment, as well as flow expansion along the exhaust pipe. An interesting feature of the temperature field is the asymmetric distribution across the exhaust cross-section, where higher temperatures are concentrated near the lower side of the exhaust pipe compared to the upper side. This phenomenon indicates that heat accumulation is not uniformly distributed, suggesting the influence of gravitational effects, flow inertia, and asymmetric flow development within the exhaust geometry.

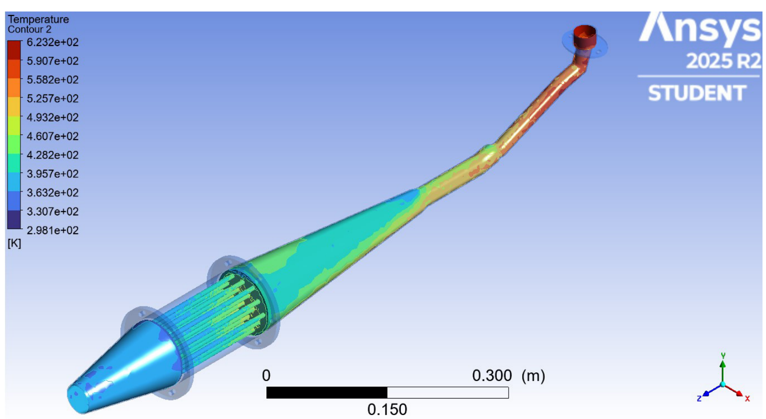


Figure 3. Temperature contour distribution of exhaust gas along the exhaust system and the 150 mm calcium carbide waste adsorber

Within the adsorber section, the temperature distribution reveals a distinct axial gradient. Higher temperatures are observed at the front region of the adsorber, where the exhaust gas first comes into contact with the calcium carbide waste material, followed by a gradual decrease toward the rear end of the adsorber. This behavior suggests that the adsorber acts as a thermal buffer, absorbing and redistributing heat as the exhaust gas passes through the porous structure. Moreover, non-uniform temperature distribution is also evident in the conical section upstream of the adsorber. In this region, the temperature in the central zone appears lower than that near the upper and lower walls. This pattern can be attributed to flow redirection and partial flow reversal occurring after the exhaust gas impinges on the adsorber surface, leading to complex mixing and localized heat transfer effects. Such flow behavior is consistent with the velocity streamline characteristics discussed in the following subsection, where recirculation and flow redistribution play an important role in shaping both the thermal and fluid dynamic fields (Zhu and Shin, 2023).

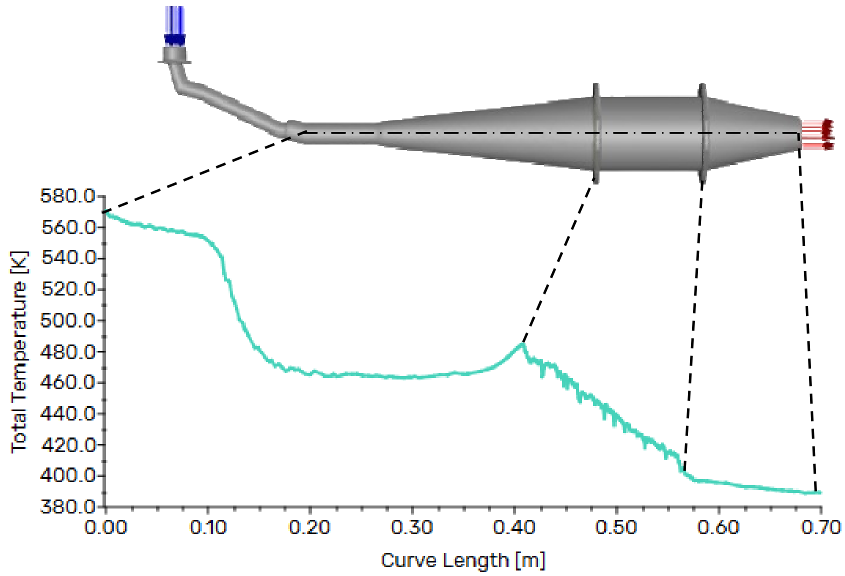


Figure 4. Axial distribution of total exhaust gas temperature along the exhaust system for the 150 mm adsorber configuration

To further clarify the thermal behavior observed in the temperature contour, Figure 4 presents the axial distribution of total exhaust gas temperature along the exhaust system for the 150 mm adsorber configuration. The profile shows a gradual temperature decrease as the exhaust gas moves downstream from the exhaust manifold, reflecting continuous heat loss due to wall heat transfer and flow development. A noticeable temperature drop is observed in the region corresponding to the conical section and the adsorber inlet, indicating enhanced thermal interaction associated with flow deceleration, mixing, and gas–solid contact. Within the adsorber, the temperature continues to decrease toward the downstream end, confirming the role of the calcium carbide waste adsorber as a thermal buffer that absorbs and redistributes heat without inducing abrupt thermal gradients.

3.2. Velocity streamline and flow development

The velocity streamline distribution for the 150 mm adsorber configuration illustrates a gradual reduction in exhaust gas velocity as the flow moves away from the exhaust manifold (Figure 5). This behavior is primarily associated with flow expansion and energy dissipation along the exhaust pipe. However, a noticeable acceleration of the exhaust gas is observed inside the adsorber section. This increase in velocity is caused by a significant reduction in flow cross-sectional area due to the presence of multiple small channels within the adsorber. According to the continuity equation and Bernoulli's principle, a decrease in effective flow area leads to an increase in flow velocity (Harefa and Giawa, 2025). Once the exhaust gas exits the adsorber, the velocity decreases again as the flow expands into a larger downstream section. The streamline visualization further reveals that the majority of the exhaust flow is concentrated near the lower side of the exhaust pipe, particularly in the conical section upstream of the adsorber. This flow concentration results in asymmetric flow development, which is later altered by the interaction between the exhaust gas and the adsorber surface.

https://doi.org/10.29303/dtm.v16i1.1247

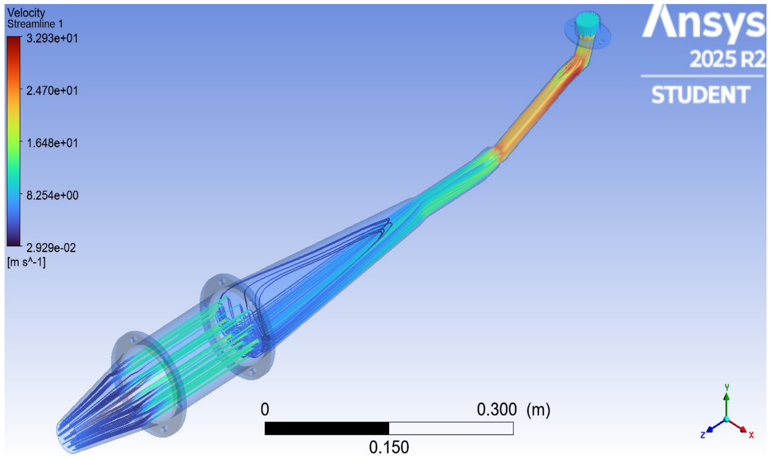


Figure 5. Velocity streamline of exhaust gas flow through the exhaust system with a 150 mm calcium carbide waste adsorber

The interaction between the exhaust flow and the adsorber induces partial flow reversal and recirculation, predominantly concentrated near the upper region of the exhaust pipe after the gas impinges on the adsorber. This flow reversal explains the non-uniform temperature distribution observed in the previous subsection, where higher temperatures were recorded near the lower part of the exhaust system. Although previous experimental studies reported a reduction in exhaust emissions with increasing adsorber length, which was attributed to longer gas–adsorber contact time, the present numerical results indicate that the exhaust gas velocity inside the adsorber increases as a result of flow constriction. This finding suggests that the effective contact duration between the exhaust gas and the adsorber material may be relatively short, despite the increased adsorber length. Consequently, future design modifications are necessary to enhance gas residence time, such as optimizing the internal geometry of the adsorber. The current adsorber design consists of 19 internal channels with a diameter of 6 mm each and an overall adsorber diameter of 88 mm. Increasing the number of internal channels or modifying their arrangement may reduce local flow acceleration and promote longer gas–solid interaction, potentially leading to more effective emission reduction.

3.3. Pressure distribution

The pressure contour for the 150 mm adsorber configuration shows a clear pressure variation along the exhaust system as shown in Figure 6. As the exhaust gas flows downstream from the exhaust manifold, a gradual pressure decrease is observed, indicating continuous energy loss due to wall friction and flow development. Local pressure drops are particularly evident at the bent sections of the exhaust pipe. These pressure reductions occur as a result of additional flow resistance caused by changes in flow direction, which induce secondary flows and increase viscous losses. Such behavior is typical in exhaust systems with geometric curvature, where momentum redistribution and flow separation contribute to localized pressure loss (Helmizar et al., 2026).

https://doi.org/10.29303/dtm.v16i1.1247

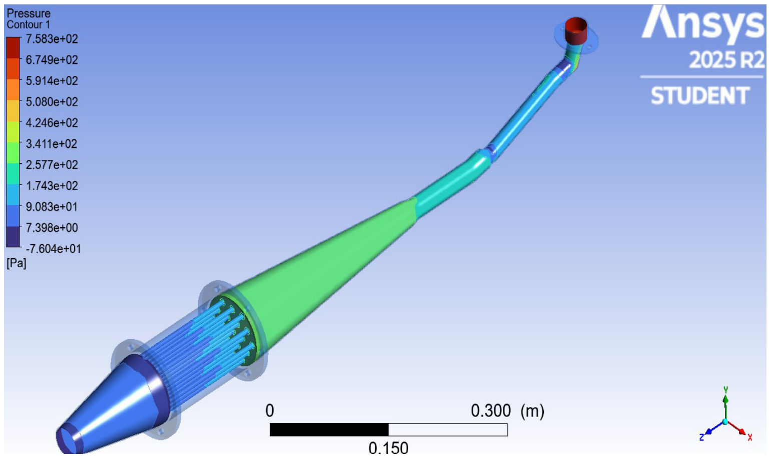
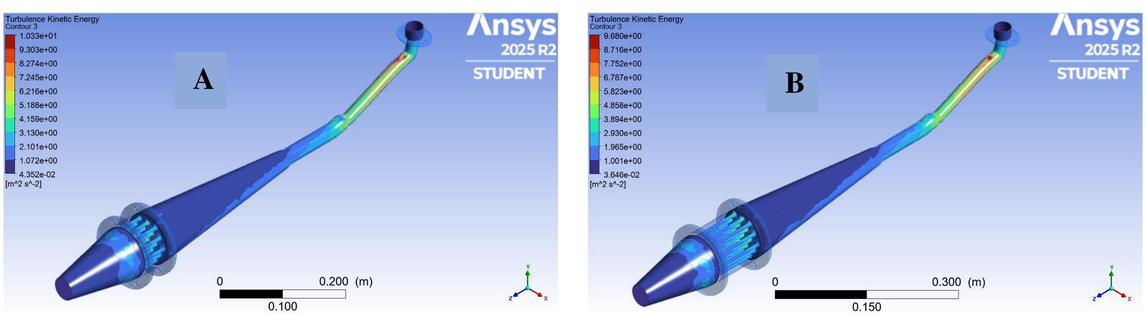


Figure 6. Pressure contour distribution along the exhaust system equipped with a 150 mm calcium carbide waste adsorber

In contrast, a pressure increase is observed in the conical section of the exhaust pipe upstream of the adsorber. This pressure rise can be attributed to flow deceleration associated with the gradual expansion of the flow passage, which converts a portion of the kinetic energy into static pressure in accordance with Bernoulli's principle. As the exhaust gas enters the adsorber, the pressure decreases significantly due to the presence of flow constrictions and the porous internal structure of the adsorber. The pressure continues to decrease toward the downstream end of the adsorber as the exhaust gas moves farther away from the source of the flow. This progressive pressure reduction indicates that the adsorber introduces additional flow resistance while still maintaining a smooth pressure gradient, suggesting that excessive back pressure is avoided. Such pressure behavior is desirable for exhaust applications, as it allows effective gas–adsorber interaction without imposing severe penalties on engine performance (Bindar, 2009).

3.4. Effect of adsorber length on turbulence kinetic energy

The turbulence kinetic energy (TKE) contours reveal noticeable differences among the three adsorber lengths, although the overall flow patterns remain similar (Figure 7). For the shorter adsorber configuration (50 mm), higher TKE values are observed compared to the longer adsorber (150 mm), particularly in the upstream egion and near the conical section of the exhaust. This behavior can be attributed to the limited flow development length in shorter adsorbers, where the exhaust gas undergoes abrupt acceleration and deceleration over a shorter distance. As a result, stronger velocity gradients and shear layers are generated, leading to increased turbulence production. In addition, the conical section of the exhaust exhibits higher TKE levels for the 50 mm and 100 mm adsorbers than for the 150 mm case. This occurs because, in shorter adsorbers, a larger portion of the flow disturbances generated at the inlet and conical transition remains energetic and has not yet been sufficiently dissipated by viscous effects before entering the adsorber.



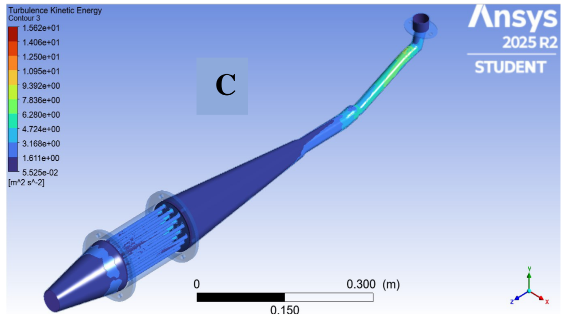


Figure 7. Turbulence kinetic energy distribution of exhaust gas flow, A) 50 mm, B) 100 mm, C) 150 mm

Despite these differences, all three adsorber configurations exhibit a consistent trend in which turbulence kinetic energy increases as the exhaust gas enters the adsorber. This increase is caused by the interaction between the high-velocity exhaust flow and the multiple small channels within the adsorber, which intensifies shear, flow separation, and local recirculation. Once the exhaust gas exits the adsorber, the TKE decreases due to flow expansion and energy dissipation. However, the downstream region of the 50 mm and 100 mm adsorbers shows a relatively larger area with elevated TKE compared to the 150 mm adsorber. This phenomenon can be explained by the shorter dissipation length available in the downstream section, which allows residual turbulence generated inside the adsorber to persist farther downstream. In contrast, the longer adsorber provides more internal surface area and flow interaction length, promoting turbulence decay before the flow exits the adsorber. These findings suggest that while shorter adsorbers generate stronger turbulence, longer adsorbers may offer a more balanced condition between turbulence enhancement and turbulence dissipation, which is beneficial for stable exhaust flow and sustained gas-solid interaction

4. CONCLUSION

This study has numerically investigated the exhaust gas flow behavior through a calcium carbide waste adsorber using computational fluid dynamics. The analysis focused on pressure distribution, velocity streamline, temperature field, and turbulence kinetic energy to provide physical insight into the internal mechanisms that cannot be directly observed through experimental measurements. The numerical results demonstrate that the exhaust system exhibits a gradual pressure reduction with localized losses at bent sections, while the conical geometry contributes to controlled pressure recovery prior to the adsorber.

Velocity streamline analysis indicates that exhaust gas accelerates within the adsorber due to flow constriction through multiple internal channels, followed by deceleration downstream of the adsorber. The temperature distribution reveals asymmetric heat concentration and a progressive temperature decrease along the adsorber length, confirming the role of the adsorber as a thermal buffer. Turbulence kinetic energy increases at the adsorber entrance for all configurations, while differences in adsorber length influence turbulence intensity and dissipation behavior. Shorter adsorbers generate higher turbulence levels, whereas longer adsorbers promote more effective turbulence decay.

Overall, the numerical findings provide a mechanistic explanation for the emission reduction trends reported in previous experimental studies and indicate that future adsorber design optimization should focus on enhancing gas residence time while maintaining balanced turbulence characteristics for improved emission control.

REFERENCES

Bindar, Y., Geometry effect investigation on a conical chamber with porous media boundary condition using computational fluid dynamic (cfd) technique, ITB Journal Engineering Science, 41(2), 97-110, 2009.

Eliopoulos, I.P., Eliopoulos, G., Sfendoni, T., Economou-Eliopoulos, M, Cycling of pt, pd, and rh derived from catalytic converters: potential pathways and biogeochemical processes, Minerals, 12, 917, 2022.

Harefa, D., Giawa, A.B., Analisis literatur tentang prinsip bernoulli dalam desain aliran fluida, Identik: Jurnal Ilmu Ekonomi, Pendidikan dan Teknik, 2(2), 22-27, 2025.

Helmizar, H., Nopita, D., Witanto, Y., Shai, K., Eka P.R.D., Mainil, A.K., Computational fluid dynamics study on head loss through 90° elbows with curvature radius variation, International Journal of Engineering, Transactions C: Applications, 39(6), 1438–1452, 2026.

https://doi.org/10.29303/dtm.v16i1.1247

Karim, M.A., Nasir, S., Widowati, T.W., Hasanudin, U., Kinetic study of adsorption of metal ions (iron and manganese) in groundwater using calcium carbide waste, Journal of Ecological Engineering, 24(5), 155–165, 2023.

Martias, Purwanto, W., Handanu, O.J., Baharudin, A., Andrizal, Analysis of modified exhaust tip geometry on flow behavior and backpressure in car exhaust systems for electricity harvesting, Advance Sustainable Science, Engineering and Technology (ASSET), 7(2), 02502020-01-02502020-010, 2025.

Patel, K.D., Subedar, D., Patel, F, Design and development of automotive catalytic converter using non-nobel catalyst for the reduction of exhaust emission: a review, Materials Today: Proceedings, 57, 2465–2472, 2022.

Soemardi, T.P., Siswantara, A.I., Erwin, Diffuser optimation at exhaust system with catalytic converter for 110 cc mopet with fluid flow cfd simulation, MAKARA Journal of Technology, 7(2), 73-82, 2010.

Sylvia, N., Sobrina, L., Nasrun, Optimasi proses penyerapan CO_2 dengan adsorben karbon aktif menggunakan computational fluid dynamics (CFD) dan response surface methodology (RSM), Jurnal Teknologi Kimia Unimal, 8(1), 69-82, 2019.

Tira, H.S, Ikhsan, D, The effect of various two-wheeler camshaft materials on dynamic response using finite element analysis, Rotasi, 25(4), 68-74, 2023.

Tira, H.S, Nuarsa, I.M., Renaldy, Designing an energy-efficient prototype vehicle by the mandalika desantara racing team, Rotasi, 26(4), 44-49, 2024.

Tira, H.S., Padang, Y.A., Syahrul, Putra, D.R.A., Mulyanto, A., Salman, Combination of biogas-dual fuel engine method and activated charcoal adsorbent to minimize emissions from two-wheeler. E3S Web of Conferences, 465, 01013, 2023.

Tira, H.S., Wirawan, M., Rahman, S., Sukjit, E., Sudirman, Performance of adsorbent from calcium carbide residue to reduce exhaust emissions of two-wheeler, Automotive Experiences, 6(1), 23–37, 2023.

Wakid, M., Widyianto, A., Widowati, A., Karakteristik panas pada exhaust manifold dengan variasi putaran mesin menggunakan computational fluid dynamics, Jurnal Pendidikan Vokasi Otomotif, 6(2), 51-70, 2024.

Zhu, R., Shin, D., Study on flow and heat transfer characteristics of 25 kw flameless combustion in a cylindrical heat exchanger for a reforming processor, Energies, 16(20), 7160, 2023.

https://doi.org/10.29303/dtm.v16i1.1247