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Hydrodynamic Resistance of a Rotary Dynamic Dust Collector Under Various Operating Conditions

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Abstract: This study investigates the hydrodynamic performance of a rotary dynamic dust collector, specifically evaluating the impact of operational variables on hydraulic resistance. Experimental trials were conducted using a laboratory-scale prototype under both dry and wet regimes. The investigation covered gas velocities from 10 to 20 m/s, rotational speeds between 400 and 600 rpm, and liquid flow rates ranging from 0.075 to 0.175 m^3/h. The findings indicate that total pressure drop is significantly intensified by increments in gas velocity, Rotor rotational speed, and irrigation rates. Specifically, under dry conditions, hydraulic resistance escalated from 107 to 487 Pa at 400 rpm, and reached 637 Pa at 600 rpm with peak gas velocity. During wet operation at 600 rpm, a maximum resistance of 1231 Pa was recorded. These phenomena are attributed to enhanced turbulence intensity induced by the rotor and additional drag forces resulting from the atomization of the liquid phase. The paper provides an in-depth engineering analysis of the governing hydrodynamic mechanisms and proposes a generalized empirical correlation for pressure drop estimation. These results offer critical insights for optimizing the structural parameters and energy efficiency of industrial rotary gas-cleaning systems.

Keywords: Rotary dynamic dust collector, hydraulic resistance, pressure drop, gas velocity, Rotor rotational speed, liquid flow rate, wet gas cleaning, dust-laden gas.

INTRODUCTION:

Industrial enterprises within the chemical, construction-materials, mineral-processing, and asphalt-concrete sectors generate considerable amounts of dust-laden gases. If such emissions are discharged directly into the atmosphere, they worsen environmental conditions, pollute the air of working areas, and create health risks for personnel and nearby populations. For this reason, the development of efficient and scientifically grounded gas-cleaning technologies with acceptable energy consumption remains an urgent engineering task.

Among modern dust-collection systems, rotary dynamic apparatuses are of particular interest because they combine several mechanisms of action in a single volume. In such devices, the gas flow experiences simultaneous mechanical, aerodynamic, and hydrodynamic effects. Due to the presence of a rotating working body, the Dust-laden gas is intensively mixed, its trajectory changes repeatedly, and favorable conditions arise for the transfer of dispersed particles into the liquid phase. However, the performance of such an apparatus cannot be evaluated only by collection efficiency. An equally important parameter is hydraulic resistance, because an increase in pressure drop directly affects fan power demand, energy consumption, and total operating cost.

Therefore, the rational design of a rotary dynamic dust collector requires a clear understanding of how the main operating parameters influence pressure loss. In practical operation, an increase in gas velocity may intensify contact and improve particle capture, but it also raises dynamic pressure and friction losses. Similarly, increasing Rotor rotational speed promotes internal circulation and turbulence, while liquid supply improves gas-liquid interaction and dust capture but simultaneously introduces additional resistance. As a result, there is a need to identify a technically justified balance between cleaning efficiency and hydraulic performance.

The purpose of this study is to investigate, on the basis of laboratory experiments, the influence of gas velocity, rotor rotational speed, and liquid flow rate on the total hydraulic resistance of a rotary dynamic dust collection apparatus. In addition to translating the original manuscript into English, the present version broadens the analysis by discussing the physical nature of the observed trends, summarizing practical implications for engineering design, and formulating an empirical representation of the dependence of pressure drop on the operating parameters.

METHODS

This section describes the experimental setup, operating conditions, and methodology used for evaluating the hydraulic resistance of the rotary dynamic dust collector.

1. Experimental apparatus.

The experiments were performed on a laboratory-scale model of a rotary dynamic dust collection apparatus. The design of the unit was developed based on a six-stage systems analysis conducted in the MATLAB environment, followed by the fabrication of a laboratory prototype. The modeling stages encompassed the gas inlet phase, the trajectory of dust-laden gas within the housing, the kinematics of the rotor and disks, internal gas stream redirection, the introduction of the working liquid, the formation of the gas-liquid contact interface, and the discharge of purified gas and slurry. This approach resulted in a functionally integrated configuration of a high-efficiency rotary spraying apparatus.

According to the operational principle shown in Figure 1, the dust-laden air enters the cylindrical housing (1) via an inlet branch pipe (2). The rotation is driven by the motor (3) connected to the shaft (4), which rotates the disks and rotor assembly (5). The disks feature specific openings for airflow passage to facilitate movement. The working liquid is introduced via a dedicated fitting (6), forming a liquid film both on the internal wall of the apparatus and within the working volume.

Under the influence of rotation, the dust-laden gas moves intensively within the active volume of the apparatus and is directed toward the housing wall. Consequently, intensive contact occurs between the gas and liquid phases, facilitating the absorption of dispersed particles by the liquid. The purified gas is subsequently removed through an upper outlet branch pipe (7), while the resulting slurry is discharged via the slurry outlet (8) located at the bottom of the conical section.

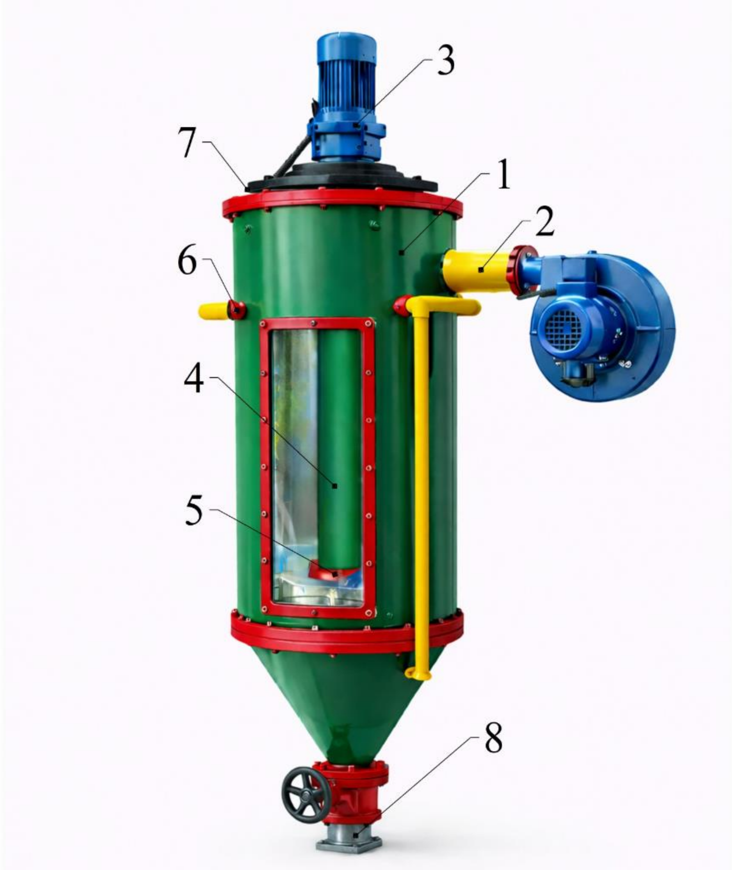

Figure 1. General view of the laboratory model of the rotary dynamic dust collection apparatus:

1 – housing; 2 – inlet pipe; 3 – motor; 4 – shaft; 5 – rotor/disks assembly; 6 – liquid inlet; 7 – gas outlet; 8 – slurry outlet.

2. Operating conditions.

The inlet gas velocity was set at increments of 10, 12, 14, 16, 18, and 20 m/s. The Rotor rotational speed was varied at 400, 500, and 600 rpm. In the wet-operating mode, the water flow rate was adjusted to 0.075, 0.125, and 0.175 m^3/h. The dry regime was employed to evaluate the aerodynamic characteristics of the apparatus, while the wet regime was used to assess hydrodynamic behavior during liquid injection. The gas flow rate corresponding to the aforementioned velocities ranged from 0.0785 to 0.1571 m^3/s (equivalent to 282.7–565.5 m^3/h). During the trials, the total hydraulic resistance, ΔPtotal, and the overall resistance coefficient, ζtotal, were determined. The experimental data were processed into comparative tables and plots to identify the individual and combined influence of the primary operating parameters.

3. Evaluation approach.

The overall resistance of the apparatus was assessed by measuring the pressure drop across the unit under fixed operating conditions. In engineering terms, the total pressure loss of a rotary dynamic gas-cleaning apparatus can be considered the cumulative effect of several factors: inlet losses, losses associated with local redirection and redistribution of the gas flow, rotor-induced circulation losses, interaction losses within the gas-liquid contact zone, and outlet losses.

In a simplified generalized form, this relationship is expressed as:

$$\Delta P_{total} = \Delta P_{in} + \Delta P_{rot} + \Delta P_{gl} + \Delta P_{out} \quad (1)$$

Although the present work focuses on experimentally measured total hydraulic resistance rather than a detailed decomposition of all components, such a representation is instrumental for understanding how variations in operating variables alter the hydrodynamic environment inside the apparatus.

RESULTS

1. Influence of gas velocity under dry operating conditions.

The experimental results clearly showed that gas velocity exerts a strong influence on the formation of hydraulic resistance in the rotary dynamic dust collector. Under dry operation, the pressure drop increased steadily with increasing gas velocity at all investigated Rotor rotational speeds. At a Rotor rotational speed of 400 rpm, the measured hydraulic resistance increased from 107 Pa at 10 m/s to 487 Pa at 20 m/s. At 500 rpm, the corresponding values increased from 126 to 561 Pa, and at 600 rpm from 145 to 637 Pa.

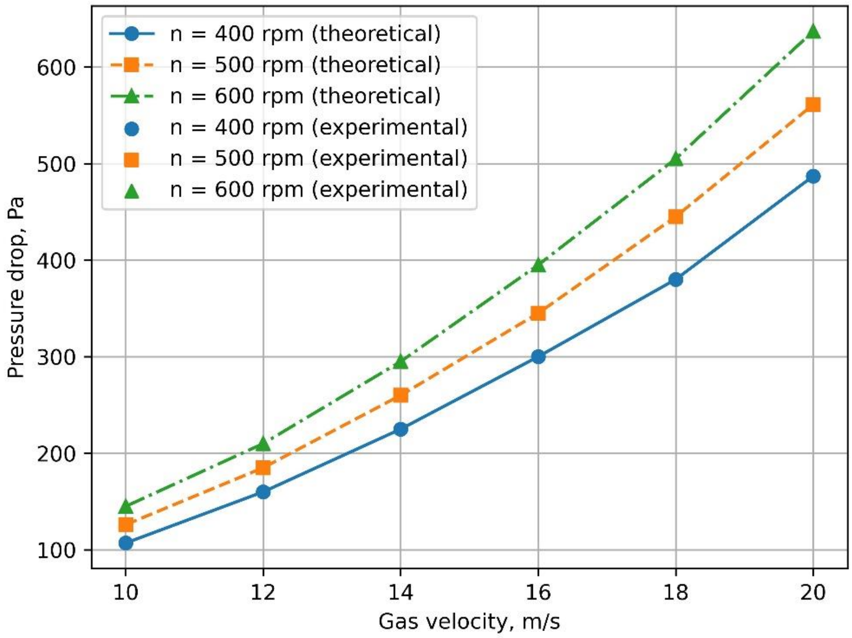

Figure 2. Influence of gas velocity and Rotor rotational speed on hydraulic resistance under dry operating conditions

The observed trend is explained primarily by the growth of the kinetic energy of the flow. As gas velocity rises, dynamic pressure increases and the intensity of local losses inside the apparatus becomes greater. In addition, the more rapid flow interacts more actively with the rotating elements and the internal surfaces of the apparatus, which intensifies momentum exchange and turbulence. Consequently, the total pressure drop rises in a parabolic dependency rather than by a simple constant increment.

Another important observation is that, at the same gas velocity, higher Rotor rotational speed consistently led to higher hydraulic resistance. This indicates that the rotor not only acts as an active internal element that redistributes the gas flow, but also serves as a source of additional hydrodynamic disturbance, which must be considered when selecting operating modes.

2. Influence of Rotor rotational speed.

In the next stage of analysis, the influence of Rotor rotational speed was evaluated separately. Increasing the Rotor rotational speed from 400 to 600 rpm caused a monotonic rise in hydraulic resistance over the entire investigated range of gas velocities. For example, at a gas velocity of 20 m/s, the hydraulic resistance increased from 487 Pa at 400 rpm to 561 Pa at 500 rpm and further to 637 Pa at 600 rpm. At a lower gas velocity of 10 m/s, the corresponding increase was from 107 to 126 and 145 Pa.

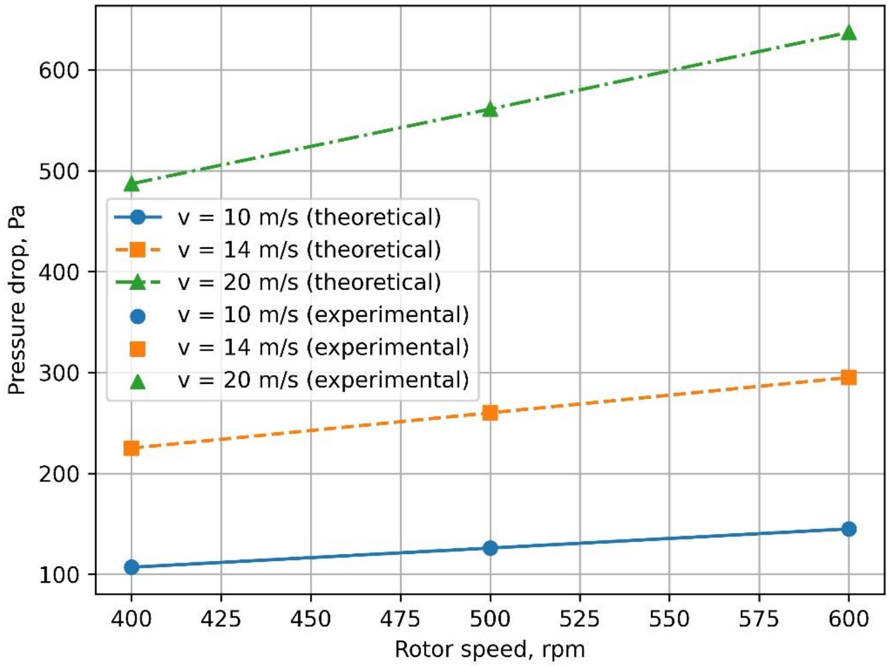

Figure 3. Influence of Rotor rotational speed on hydraulic resistance

This behavior can be explained by the fact that higher Rotor rotational speed intensifies the internal swirl, promotes more complex circulation trajectories, and strengthens turbulence generation. As the rotating elements accelerate, the gas flow experiences repeated redirection and stronger local interactions with the rotor-disks assembly. These mechanisms increase local hydrodynamic losses and contribute to a larger total pressure drop.

From a practical standpoint, the result is significant because Rotor rotational speed is often treated as a convenient control parameter for intensifying contact processes. However, the current experiments show that the advantage of improved mixing is accompanied by additional energy losses. Therefore, increasing Rotor rotational speed should be justified not only by its potential effect on dust capture, but also by the corresponding increase in hydraulic resistance.

3. Influence of liquid flow rate in wet operation.

In wet operation, the influence of water flow rate was studied additionally at a Rotor rotational speed of 600 rpm. The results demonstrated that, at all investigated gas velocities, increasing the water flow rate caused an increase in hydraulic resistance. At a gas velocity of 20 m/s, the pressure drop rose from 1132 Pa at a water flow rate of 0.075 m3/h to 1182 Pa at 0.125 m3/h and to 1231 Pa at 0.175 m3/h. At a gas velocity of 14 m/s, the hydraulic resistance increased from 526 to 551 and 575 Pa over the same liquid-flow range.

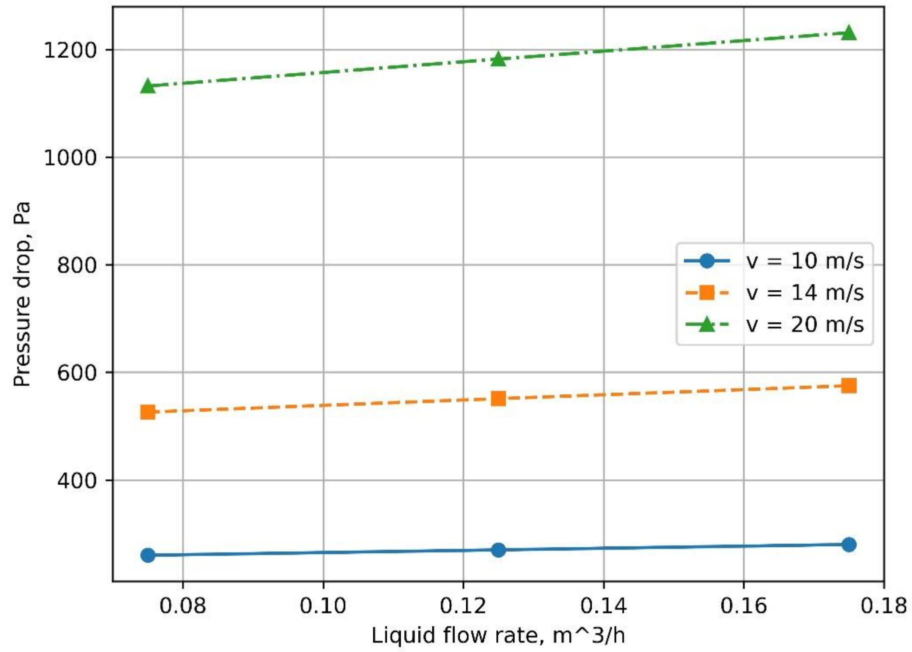

Figure 4. Influence of liquid flow rate on hydraulic resistance at a Rotor rotational speed of 600 rpm

This pattern is associated with the formation of a thicker liquid film on the apparatus wall and a greater number of droplets inside the active volume. Both effects increase the resistance encountered by the gas stream. The gas must expend additional energy to overcome drag related to interfacial interaction, droplet entrainment, and the deformation or displacement of liquid structures. At the same time, the increase in liquid flow rate enlarges the gas-liquid contact surface, which is favorable for particle capture. Thus, wet operation introduces a classic engineering trade-off: stronger mass-transfer conditions are accompanied by higher pressure losses.

3.4. Generalized experimental interpretation.

Taken together, the results indicate that the hydraulic resistance of the rotary dynamic dust collector is formed in a stepwise and interrelated manner. First, gas velocity determines the overall energetic state of the gas flow and strongly influences dynamic pressure. Second, rotor motion complicates the internal structure of the flow and adds circulation-induced losses. Third, in wet mode, liquid injection introduces an additional hydrodynamic factor that substantially increases resistance while creating more favorable conditions for gas-liquid interaction.

The data also show that the transition from dry to wet operation significantly changes the pressure-drop level. At high gas velocity and high Rotor rotational speed, the hydraulic resistance in wet mode is much greater than in dry mode. This difference confirms that the hydrodynamic behavior of a rotary dynamic scrubber cannot be described solely by the characteristics of the gas phase; the liquid phase and the gas-liquid interaction zone must also be taken into account when selecting the operating regime.

DISCUSSION

1. Physical interpretation of pressure-drop growth

The obtained results confirm that the hydraulic resistance of a rotary dynamic dust collection apparatus is governed by a multi-factor process. The sharp increase in resistance with gas velocity is typical of systems in which inertial and turbulent losses dominate. Since the gas passes through a confined apparatus volume containing rotating internal elements, any increase in velocity intensifies local accelerations, vortex formation, and friction interactions with both the housing and rotor components.

The effect of Rotor rotational speed has a somewhat different physical nature. Whereas gas velocity primarily changes the kinetic energy of the main stream, Rotor rotational speed modifies the internal organization of the flow. The rotating elements create additional swirl and recirculation zones, which lengthen the effective flow path and increase the number of local disturbances. Thus, even at constant gas throughput, a higher Rotor rotational speed leads to higher pressure loss.

The effect of liquid flow rate becomes especially important in wet operation. The introduction of liquid creates a two-phase flow regime in which the gas must move through a medium containing droplets, splashes, and liquid films. In such a system, pressure loss is determined not only by the single-phase gas dynamics, but also by interphase momentum exchange. Therefore, the rise in hydraulic resistance with increasing water flow rate is both expected and physically justified.

2. Engineering implications.

The practical significance of these findings is considerable. In industrial operation, designers and plant engineers often seek to increase gas-cleaning efficiency by intensifying the process. This can be achieved by increasing gas velocity, Rotor rotational speed, or water flow rate. However, all three measures simultaneously increase hydraulic resistance and, consequently, energy demand. Therefore, the apparatus should not be operated solely at the highest possible regime. Instead, a compromise must be found between cleaning efficiency and acceptable pressure drop.

From the presented data, it follows that gas velocity is the most influential parameter with respect to hydraulic resistance. Rotor rotational speed has a distinct but secondary contribution, whereas liquid flow rate mainly determines the difference between dry and wet operation and controls the degree of gas-liquid contact. Accordingly, a rational approach to optimization would be to select a moderate gas velocity, then adjust Rotor rotational speed and liquid flow rate in accordance with the required cleaning performance.

3. Empirical form of the dependence

Based on the experimental observations and regression analysis of the full data set, the dependence of the total hydraulic resistance on the main operating parameters was formulated in a generalized empirical form:

$$\Delta P_{total} = av^2 + bn + cQ_{liq} + d \qquad (2)$$

Through multivariate nonlinear regression, the following empirical coefficients were determined with a high correlation coefficient of $R^2 = 0.98$: a = 1.07: Represents a structural constant related to the apparatus geometry and configuration. b = 2: Reflects the dominant nonlinear (nearly quadratic) influence of gas velocity on pressure drop, characteristic of turbulent flow regimes. c = 0.75: Accounts for the linear contribution of the rotor speed (*n*) to the overall resistance due to internal swirl. d = 2850: Reflects the impact of the liquid irrigation rate (Q_{liq}), accounting for additional drag forces in the gas-liquid interaction zone.

This expression accurately captures the observed tendencies where gas velocity remains the primary governing factor, while rotor motion and liquid injection provide incremental contributions. The correlation serves as a reliable engineering tool for predicting the hydraulic performance and provides a framework for scaling the apparatus to industrial conditions.

4. Limitations and prospects for further study.

The current work was carried out on a laboratory-scale model and focused primarily on the hydraulic aspect of apparatus operation. For complete industrial substantiation, the pressure-drop data should later be coupled with dust-collection efficiency, fractional particle-capture behavior, and specific energy consumption. In addition, further research could include a wider range of rotor geometries, liquid-distribution patterns, and inlet-dust concentrations. Such studies would allow the development of more comprehensive optimization criteria for the rotary dynamic dust collection process.

CONCLUSIONS

The conducted investigation successfully quantified the influence of key operational parameters on the hydraulic resistance of a rotary dynamic dust collection apparatus. The following conclusions can be drawn from the study:

Gas velocity was identified as the primary factor governing pressure loss across all investigated conditions. An increase in gas velocity results in a pronounced escalation of hydraulic resistance, significantly influencing the energy requirements of the system.

Elevated Rotor rotational speeds intensify internal turbulence and rotational motion within the apparatus. This intensification leads to higher local hydrodynamic losses and, consequently, an increase in the overall pressure drop.

Under wet operating conditions, an increased liquid flow rate further augments hydraulic resistance. This is attributed to the formation of liquid films and droplets which, while expanding the gas-liquid contact interface, introduce additional drag forces.

The maximum recorded hydraulic resistance reached 1231 Pa under the most intensive operating parameters investigated in this work (maximum gas velocity, Rotor rotational speed, and liquid flow rate).

The findings provide a scientific foundation for optimizing apparatus design and selecting rational operating regimes. These results are critical for achieving an optimal balance between dust collection efficiency and energy consumption.

In summary, the hydraulic performance of a rotary dynamic dust collector is dictated by the synergistic effects of gas-dynamic forces, rotor-induced motion, and gas-liquid interactions. These results serve as a theoretical and practical basis for the future enhancement and industrial scale-up of rotary-type gas-cleaning equipment.

Nomenclature

Symbol	Description	Unit
ΔP_{total}	Total hydraulic resistance (total pressure drop)	Pa
ζ_{total}	Overall resistance coefficient	dimensionless
v	Gas velocity	m/s
n	Rotor rotational speed	rpm
Q_{liq}	Liquid flow rate	m^3/h
ρ	Gas density	kg/m^3
ΔP_{in}	Pressure loss at the inlet section	Pa
ΔP_{rot}	Pressure loss due to rotor-induced circulation	Pa
ΔP_{gl}	Pressure loss in the gas-liquid contact zone	Pa
ΔP_{out}	Pressure loss at the outlet section	Pa

AI Use Disclosure

The authors used ChatGPT (OpenAI) to assist with English language editing and translation. All scientific interpretations, results, and conclusions were developed by the authors and carefully reviewed.

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