

Desulfurization of Flue Gases from Medium-Capacity Gas-Piston Power Plants Using Spiral-Vortex Equipment with Reduced Aerodynamic Resistance

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Abstract. The purpose of this study is to justify the design parameters of spiral-vortex equipment ensuring energy-efficient desulfurization of flue gases from autonomous medium-capacity gas-piston power plants (GPPPs). The study is driven by the necessity to reduce the aerodynamic resistance of gas cleaning systems to minimize the parasitic load on power units. To achieve this, the following tasks were addressed: developing a mathematical model of gas phase motion in a macro-scale curvilinear channel; conducting numerical modeling of the evolution of secondary macro-vortex structures; and determining the influence of the spiral inclination angle and velocity regimes on mass transfer intensity. The research methodology is based on computational fluid dynamics (CFD) approaches for analyzing turbulent flows under centrifugal forces acting on exhaust gases. The most significant result is establishing the possibility of stable liquid film formation and intense macro-vortices at low aerodynamic resistance (up to 400 Pa). It is demonstrated that at an optimal flow velocity of 6.0 m/s and a scrubber cross-sectional area of 0.9 m², a maximum SO₂ absorption efficiency (above 96%) is achieved without auxiliary induced-draft fans. The scientific and practical significance lies in creating an engineering design methodology for compact gas cleaning equipment for distributed power generation. The proposed design solutions provide annual electricity savings of 65–95 thousand kWh per 2.6–3.0 MW power unit, significantly increasing the overall profitability and environmental safety of autonomous energy centers.

Keywords: wet scrubber, desulfurization, GPPP, energy efficiency, macro-vortex structures, aerodynamic resistance, distributed generation.

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Desulfurarea gazelor de ardere din centralele electrice cu piston pe gaz de capacitate medie utilizând echipamente spirale-vortex cu rezistență aerodinamică redusă

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Rezumat. Scopul acestui studiu este fundamentarea parametrilor de proiectare ai echipamentelor spiral-vortex care asigură desulfurarea eficientă din punct de vedere energetic a gazelor de eşapament ale centralelor electrice autonome cu piston pe gaz (GPPP) de capacitate medie. Actualitatea studiului este determinată de necesitatea reducerii rezistenței aerodinamice a sistemelor de epurare a gazelor pentru a minimiza sarcina parazitară asupra unităților de putere. Pentru a realiza acest lucru, au fost abordate următoarele sarcini: elaborarea unui model matematic al mișcării fazei gazoase într-un canal curbiliniu la scară macro; efectuarea modelării numerice a evoluției structurilor secundare macro-vortex; și determinarea influenței unghiului de înclinare spirală și a regimurilor de viteză asupra intensității transferului de masă. Metodologia de cercetare se bazează pe abordări de dinamică computațională a fluidelor (CFD) pentru analiza fluxurilor turbulente sub forțe centrifuge care acționează asupra gazelor de eşapament. Cel mai semnificativ rezultat este stabilirea posibilității formării unei pelicule lichide stabile și a macro-vortexurilor intense la rezistență aerodinamică scăzută (până la 400 Pa). Se demonstrează că la o viteză optimă de curgere de 6,0 m/s și o secțiune transversală a scrubberului de 0.9 m², se obține o eficiență maximă de absorbție a SO₂ (peste 96%) fără ventilatoare auxiliare cu tiraj indus. Semnificație. Importanța științifică și practică constă în crearea unei metodologii de proiectare inginerească pentru echipamente compacte de purificare a gazelor pentru generarea distribuită de energie electrică. Soluțiile de proiectare propuse oferă economii anuale de energie electrică de 65-95 mii kWh per unitate de putere de 2.6-3.0 MW, crescând semnificativ profitabilitatea generală și siguranța de mediu a centrelor energetice autonome.

Cuvinte-cheie: scrubber umed, desulfurization, energy efficiency, macrovortex structures, aerodynamic resistance, distributed generation.

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Десульфуризация выхлопных газов ГПЭС средней мощности с использованием спирально-вихревого оборудования с пониженным аэродинамическим сопротивлением

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Аннотация. Целью данной работы является обоснование конструктивных параметров спирально-вихревого оборудования, обеспечивающего энергоэффективную десульфуризацию выхлопных газов автономных газопоршневых электростанций (ГПЭС) средней мощности. Актуальность исследования обусловлена необходимостью снижения аэродинамического сопротивления систем газоочистки для минимизации паразитной нагрузки на энергоблоки. Для достижения поставленной цели решены следующие задачи: разработка математической модели движения газовой фазы в криволинейном канале макро-масштаба; проведение численного моделирования эволюции вторичных макро-вихревых структур; определение влияния угла наклона спирали и скоростных режимов на интенсивность массообмена в оборудовании. Методология исследования базируется на использовании подходов вычислительной гидродинамики (CFD) для анализа турбулентных потоков в условиях действия центробежных сил на выхлопные газы. Наиболее важным результатом является установление возможности стабильного формирования жидкостной пленки и интенсивных макровихрей при низком аэродинамическом сопротивлении (до 400 Па) установки. На примере показано, что при оптимальной скорости потока 6.0 м/с и площади рабочего сечения скруббера (0.9 м²), достигается максимальная эффективность абсорбции SO₂ (свыше 96%) без использования вспомогательных дымососов. Научная и практическая значимость работы заключается в создании инженерной методики проектирования компактного газоочистного оборудования для распределенной энергетики и предложенные конструктивные решения обеспечивают годовую экономию электроэнергии в размере 65–95 тыс. кВт·ч на один энергоблок мощностью 2.6–3.0 МВт, что существенно повышает общую рентабельность и экологическую безопасность автономных энергоцентров.

Ключевые слова: мокрый скруббер, десульфуризация, ГПЭС, энергоэффективность, макровихревые структуры, аэродинамическое сопротивление, распределенная генерация.

INTRODUCTION

The problem of atmospheric air pollution by organic fuel combustion products at thermal power plants and distributed generation facilities remains one of the most acute issues on the global environmental agenda. According to comprehensive reviews of environmental impacts [1], gaseous pollutant emissions exert a systemic destructive influence on the biosphere. The World Health Organization (WHO) Global Air Quality Guidelines [2] establish stringent maximum permissible concentrations for sulfur dioxide (SO₂) and nitrogen oxides (NO_x), the exceeding of which leads to serious consequences [3]. At the legislative level, these requirements are enshrined in Directive 2010/75/EU [4], which mandates enterprises to transition to Best Available Techniques (BAT). In the field of flue gas desulfurization (FGD), wet scrubbers have been recognized as the global standard [5]. However, their operation at modern gas-piston power plants (GPPPs) is associated with colossal energy losses. As noted in the analysis of emission reduction technologies [6], cleaning systems are the primary consumers of auxiliary electricity, utilizing a significant portion of power to overcome aerodynamic resistance. In modern autonomous energy systems based on

medium-capacity GPPPs, the energy "penalty" for using cleaning systems directly affects specific fuel consumption [7] and the overall economic efficiency of the power units [8]. Traditional equipment creates high hydraulic resistance (1200–2000 Pa), requiring the installation of energy-intensive induced-draft fans. The solution to this problem lies in the field of hydrodynamic process intensification. Transitioning to curvilinear channels allows for the utilization of secondary flow physics described by Dean and Hurst [9]. Spiral configurations intensify mass transfer [10] through the generation of stable vortex structures [11]. However, the majority of research is focused on micro- and millimeter-scale channels [12], where classical Dean vortices are realized. Direct scaling of such solutions for industrial needs faces the problem of liquid film instability at significant gas flow rates. The scientific challenge of this work lies in creating macro-scale equipment capable of operating effectively with flow rates up to 25,000 m³/h (corresponding to typical 2.6–3 MW power units). In such conditions, classical pressure drop prediction models [13] require revision, taking into account the turbulent regime in large-section channels (0.9 m²). The scientific novelty of the work lies in the transition from microchannel systems based on Dean vortices to macroscale

industrial equipment with a synthesized structure of secondary macro-vortex flows, enabling a high degree of cleaning at anomalously low hydraulic resistance.

Accurate calculation of friction coefficients [14] and consideration of resistance data [15] are critical for preventing increases in energy costs. Modern approaches to industrial intensification [16] and the use of innovative contact devices [17] pave the way for creating compact absorbers. In the context of "clean energy," hydrodynamic optimization is recognized as a key factor in the development of distributed generation [18]. Studying flow dynamics at high Reynolds numbers [19] shows that in macro-channels, the flow structure forms macro-vortices. The synthesis of such structures in large-section equipment allows for achieving a high degree of cleaning at anomalously low aerodynamic resistance—up to 400 Pa. This enables the complete elimination of induced-draft fans, utilizing only the GPPP backpressure. The present work is aimed at bridging the gap between the theory of microchannel contactors and the needs of the power industry for large-scale, energy-efficient systems [20].

MATHEMATICAL MODEL

To assess the energy efficiency of the spiral scrubber, a model has been developed describing the gas phase motion and associated energy losses under macro-scale vortex flow conditions.

Equations of motion and turbulence

The gas dynamics of the process are described by the system of Navier-Stokes equations. Considering the high Reynolds numbers ($Re \approx 2.52 \cdot 10^5$) typical for the exhaust systems of modern GPPPs, the $k-\omega$ SST turbulence model is used, which is verified for spiral-wound heat exchangers [21] and wet cleaning systems [22]. The gas phase motion in the spiral channel is described by the system of mass and momentum conservation equations:

$$\frac{\partial g_i}{\partial x_i} = 0 \quad (1)$$

$$\rho \left(\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} \right) = - \nabla p + \mu \nabla^2 \mathbf{v} + \mathbf{f} \quad (2)$$

where,

ρ is the density of the flue gas, kg/m^3 ;

\mathbf{v} is the flow velocity vector, m/s ;

t is the time, s (for stationary calculation $\frac{\partial \mathbf{v}}{\partial t} = 0$);

∇p is the pressure gradient determining the hydraulic resistance of the apparatus, Pa/m ;

μ is the dynamic viscosity of the medium, $\text{Pa}\cdot\text{s}$;

∇^2 (or Δ) is the Laplace operator;

\mathbf{f} is the vector of external forces.

The use of this system of equations under the assumption of an incompressible medium ($\rho = \text{const}$) is justified by the low Mach numbers in the operating velocity range (3.8–7.7 m/s).

Hydrodynamics of spiral flow

The main optimization parameter in this study is the Dean number (De), which serves as the primary criterion for assessing the intensity of the synthesized macro-vortex structures. Unlike microfluidic systems, in macro-scale equipment, the Dean number characterizes not only the presence of secondary flows but also the degree of their influence on mass transfer intensification and centrifugal phase separation:

$$De = Re \cdot \sqrt{\frac{d_h}{2R}} \quad (3)$$

where,

d_h is the hydraulic diameter;

R is the radius of the spiral curvature.

The mathematical description of energy losses during gas motion in the spiral structure is based on the calculation of the pressure drop (ΔP). The total aerodynamic resistance of the determined through the resistance coefficient λ_s , adapted for macro-scale curvilinear structures based on verified engineering methodologies [14,21]:

$$\Delta P = \lambda_s \frac{L}{d_h} \frac{\rho g^2}{2} \quad (4)$$

To determine the friction coefficient under conditions of developed turbulence, characteristic of GPPP operating modes (velocity range 3.8–7.7 m/s), a modified Ito's formula is utilized. This dependency accounts for additional energy dissipation due to the generation of secondary macro-vortex flows, allowing for high-precision prediction of the target resistance indicator within the 400 Pa limit:

$$\lambda_s = \frac{0.316}{\text{Re}^{0.25}} \left[\text{Re} \left(\frac{d_h}{2R} \right)^2 \right]^{0.05} \quad (5)$$

The application of this mathematical framework allows for the justification of the spiral geometry selection, ensuring the maximum phase contact surface area at an anomalously low resistance. This is a key factor in enhancing the energy efficiency of gas cleaning systems for distributed generation.

Energy indicators of TPP

For autonomous gas-piston power plants (GPPPs), a critical parameter is the power loss for auxiliary needs (N_{loss}), which is calculated based on the volumetric flue gas flow rate Q :

$$N_{\text{loss}} = \frac{Q \cdot \Delta P}{\eta_{\text{fan}}} \quad (6)$$

where η_{fan} is the efficiency of the induced-draft fan.

The calculations also incorporate gas dust concentration and humidity parameters, which influence the effective density of the mixture and the required degree of cleaning [23]. Optimization of the channel cross-sectional area (0.9 m²) and the spiral inclination angle α enables the identification of a regime where particle separation and gas

absorption occur most effectively while achieving the target aerodynamic resistance of 400 Pa. This minimizes N_{loss} values, which is consistent with modern environmental safety concepts [24] and the principles of minimizing the Total Cost of Ownership (TCO) [27], enabling the system to operate without auxiliary induced-draft fans.

NUMERICAL INVESTIGATION AND RESULTS

Numerical Experiment Methodology

To evaluate the energy efficiency of the proposed design, flow modeling was performed in a spiral channel using parameters characteristic of the exhaust systems of modern gas-piston power plants (GPPPs). Unlike traditional studies focused on low flow rates in microchannels, this work uses a typical 2.6 MW co-generation unit as the simulation object, which is widely utilized in the distributed generation sector. This allowed for the verification of the model under industrial conditions with significant gas cleaning volumes. The main technical characteristics of the GPPP used as boundary conditions for the numerical simulation are presented in Table 1. The use of these parameters enabled the investigation of the flow structure across a wide range of engine loads (50–100%), corresponding to gas velocities in the channel ranging from 3.8 to 7.7 m/s.

Table 1¹.

Initial data and boundary conditions for numerical process simulation².

Parameter	Unit	Value (100% load)
Electrical power	kW	2600
Volumetric flue gas flow rate	m ³ /h	25 000
Flue gas temperature (outlet)	°C	380 – 420
Max. permissible exhaust backpressure	Pa	1500 – 2000
Spiral channel cross-sectional area	m ²	0.9
Flue gas dynamic viscosity (at 400°C)	Pa·s	3.1·10 ⁻⁵

The numerical mesh was optimized for the correct resolution of the boundary layer and macro-vortex structures, which is critical for accurate pressure

drop prediction in designs with curvilinear geometry [26]. The logical structure of the conducted research is presented in Fig. 1.

^{1,2}Appendix 1

The optimization process is divided into five key stages: from forming the input data array based on the characteristics of a typical GPPP to the final verification of results using the complex energy efficiency criterion ξ .

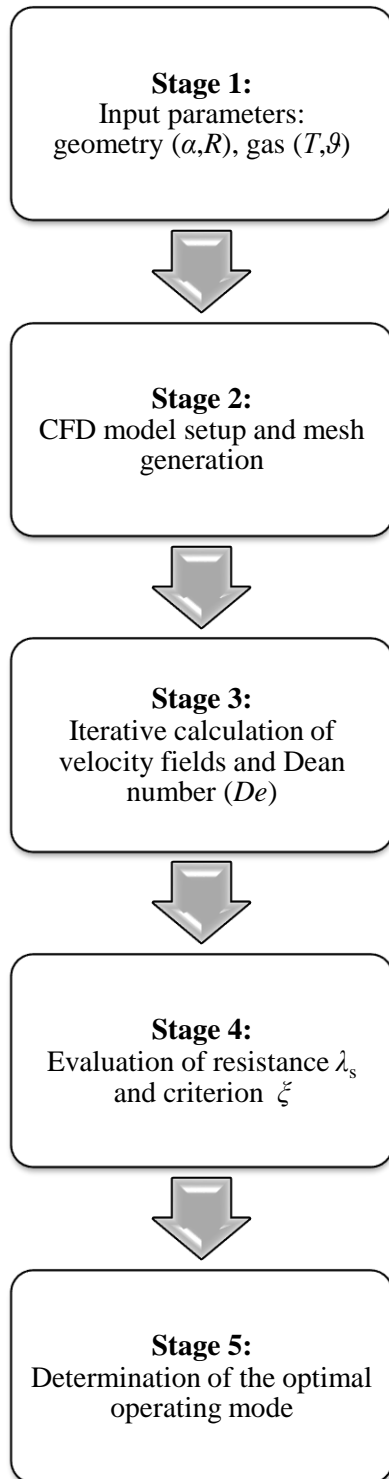


Fig. 1. Algorithm for numerical simulation and optimization of scrubber parameters.³

The key advantage of the proposed algorithm is the iterative search for a spiral geometry (inclination angle α and radius of curvature R) that ensures a target aerodynamic resistance of no more than 400 Pa. This value represents less than 25% of the maximum allowable backpressure for a medium-capacity gas engine, which guarantees the maintenance of the GPPP's rated power characteristics and enables the complete elimination of auxiliary induced-draft fans from the process flow. The implementation of this approach facilitates the transition from theoretical models to the design of reliable industrial gas cleaning systems that combine high desulfurization efficiency with anomalously low energy consumption for the GPPP's auxiliary needs.

Design Features and Innovative Liquid Distribution Mechanism

The design of the proposed unit is based on the concept of distributed film irrigation, which eliminates the use of traditional nozzle systems typical for hollow scrubbers and Venturi towers. Instead, a method of dynamic liquid film stabilization is applied: through tangential inlet and centrifugal acceleration, the absorbent is uniformly distributed along the periphery of the spiral channel. This approach allows for minimizing the diffusion resistance of the gas phase without additional energy costs for the mechanical atomization of droplets. The absence of direct hydraulic shock in the contact zone and the maintenance of film continuity are key factors in achieving the target energy efficiency with anomalously low pressure losses (up to 400 Pa). Unlike traditional nozzle systems, this design implements the principle of forming a stable film on the external wall of the spiral under the action of centrifugal forces generated by the macro-vortex flow. This avoids pressure losses typically spent on overcoming the resistance of the spray plume and eliminates the risk of secondary liquid entrainment. The distributed phase inlet ensures the maximum interfacial contact surface while maintaining macroscopic flow stability, which is critical for operating with the flue gases of autonomous power units across a wide range of loads. Experimental testing of the developed prototype indicates that this synergy of design and fluid dynamics establishes a solid basis for high purification efficiency in autonomous power systems.

³Appendix 1

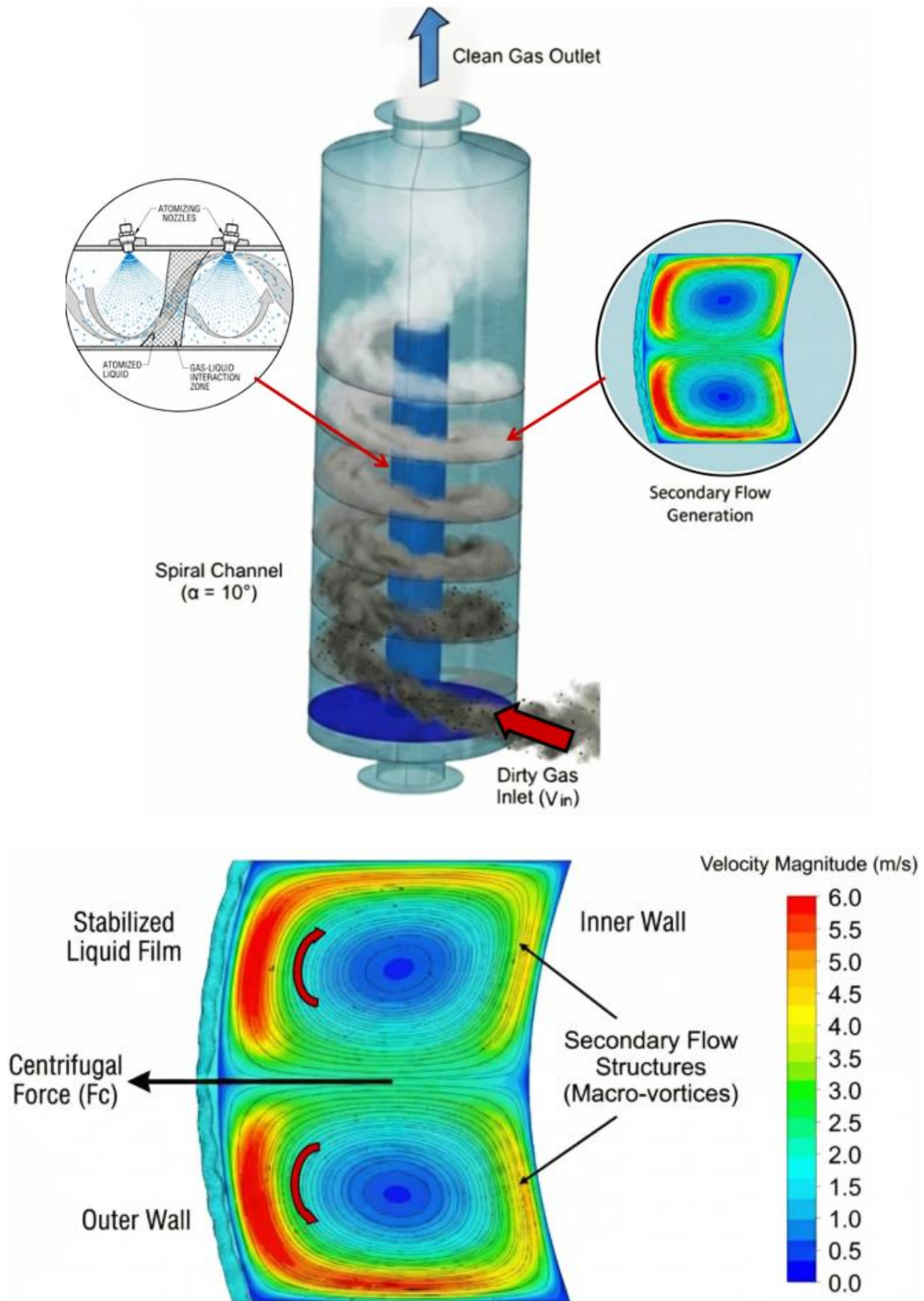


Fig. 2. Innovative spiral-vortex apparatus: a) general layout; b) velocity distribution map in the channel cross-section (visualization of secondary flow structures).⁴

⁴Appendix 1

Influence of Geometry on Hydraulic Resistance

One of the key factors determining the GPPP’s auxiliary energy consumption for gas cleaning is the spiral inclination angle α . The study found that as α increases from 5° to 20° , the structure of secondary flows undergoes significant changes. The plots of the hydraulic resistance coefficient λ_s versus the Dean number De clearly show an inflection point. For the industrial Reynolds number range investigated ($Re \approx 2.52 \cdot 10^5$), corresponding to a channel cross-section of 0.9 m^2 , the optimal angle is $\alpha=10^\circ$. At this value, stable generation of macro-vortex structures is achieved, providing intensive mass transfer (SO_2 absorption) with minimal increase in resistance. A further increase in the inclination angle leads to the dissipation of vortex energy and an increase in turbulent fluctuations. This places an unnecessary load on the engine exhaust system without a significant gain in cleaning efficiency, correlating with data for high-flow-density separators [24].

Optimization of Pressure Losses

A comparative analysis of the pressure drop ΔP in the spiral unit versus a traditional Venturi scrubber at the same gas throughput ($25.000 \text{ m}^3/\text{h}$) demonstrated the clear advantage of the spiral geometry. In traditional systems, the bulk of the energy is spent on creating high velocity in the throat (up to $60\text{--}100 \text{ m/s}$) for the mechanical atomization of liquid droplets. In the spiral scrubber, the primary phase mixing is performed by centrifugal forces at significantly lower gas velocities (up to 7.7 m/s).

Calculation results show that using a spiral channel with a 0.9 m^2 cross-section and an optimal pitch allows for reducing ΔP to the level of 400 Pa , which is $60\text{--}70\%$ lower than the resistance of standard wet cleaning systems. In

absolute terms, for a single power unit with a rated electrical capacity of 2.6 MW , this is equivalent to electricity savings in the range of $8\text{--}12 \text{ kW}$ by eliminating the auxiliary induced-draft fan from the circuit. Considering the continuous operation cycle of a GPPP (approximately 8000 h/year), the annual electricity savings for auxiliary needs amount to $65\text{--}95$ thousand kWh per unit, significantly increasing the unit's Fuel Utilization Factor (FUF).

Analysis of Operational Reliability and Energy Efficiency

The energy efficiency of the system is inextricably linked to its operational life. Intensive hydrodynamic regimes required for high-quality gas cleaning inevitably lead to erosion-corrosion wear of the structure walls. The application of mechanistic wear models [27] and practical assessments of erosive damage [28] allowed for determining that at the optimal angle of $\alpha=10^\circ$ for the 0.9 m^2 channel, the velocity profile is distributed more uniformly. This reduces local wear peaks in flow turning zones, which are characteristic of complex piping systems [29]. The reduction in wear intensity directly impacts energy efficiency: maintaining wall smoothness (absence of cavities and corrosion roughness) allows for maintaining the design hydraulic resistance of 400 Pa over a long service life (more than 5 years until major overhaul), as confirmed by numerical modeling of erosion in curved channels [30].

Comparative Analysis of Energy Characteristics

To assess the effectiveness of the spiral-vortex equipment, its characteristics were compared with industrial analogs at a nominal gas velocity corresponding to 100% load of a medium-capacity GPPP ($v=7.7 \text{ m/s}$).

Table 2⁵.

Comparative indicators of gas cleaning systems (at $v=7.7 \text{ m/s}$)⁶.

Parameter	Venturi scrubber	Packed column	Spiral unit
Total hydraulic resistance, Pa	3500 – 5000	1200 – 1800	380 – 420
SO ₂ removal efficiency, %	96 – 98	92 – 95	95.6 – 97
Specific pressure drop per meter of height, Pa/m	1200+	400 – 600	~45 – 60
Flow regime	Highly turbulent (throat)	Confined (film-flow)	Macrovortex

^{5,6}Appendix 1

The main advantage of the spiral geometry is achieving a high degree of absorption at velocities of 3.8–7.7 m/s, where traditional equipment either loses efficiency (hollow columns due to liquid entrainment) or requires a critical pressure drop for liquid atomization (Venturi scrubbers). As seen from Table 2, the proposed technical solution allows for a 3- to 8-fold reduction in specific energy consumption for cleaning compared to traditional solutions used in distributed generation. This is achieved by eliminating zones of extreme turbulence in the throat and the absence of a dense packing layer that creates parasitic resistance [15]. The application of the macro-vortex effect enables

efficient utilization of the kinetic energy of the engine's own exhaust flow, making the system autonomous and eliminating the need for additional induced-draft fans.

Analysis of Graphical Dependencies

Figure 3 illustrates the dependence of the hydraulic resistance coefficient λ_s on the Dean number De at various spiral inclination angles α . The analysis of the curves shows that in the GPPP operating range, corresponding to developed turbulent flow and high Dean numbers ($De > 5 \cdot 10^4$), a stabilization of the resistance coefficient growth is observed, which is particularly pronounced for the optimal angle $\alpha=10^\circ$.

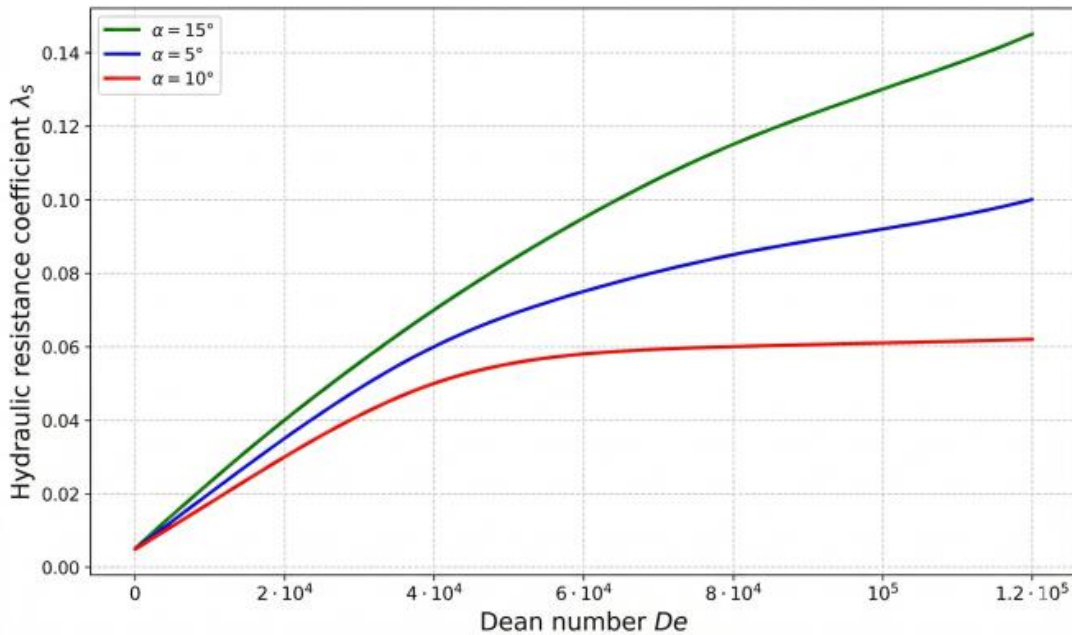


Fig. 3. Dependence of the hydraulic resistance coefficient λ_s on the Dean number (De) in the macro-vortex flow range.⁷

This confirms the hypothesis regarding the formation of a stable macro-vortex structure that organizes the flow and prevents an avalanche-like increase in friction losses at high velocities, aligning with the principles of Ito's theory for curvilinear channels [14].

Figure 4 displays the complex energy efficiency indicator ξ , which accounts for the balance between the cleaning degree and the energy expended. In contrast to high-pressure Venturi units, which require throat velocities of 60–100 m/s, the optimum of the developed unit is shifted

toward the moderate velocities characteristic of GPPP exhaust tracts. As seen from the graph, the peak efficiency occurs in the range of 5.5–6.0 m/s, corresponding to the most frequent operating mode of the power unit (approximately 75% load). With a further increase in velocity to the nominal 7.7 m/s, the efficiency decreases slightly; however, the aerodynamic resistance remains within the target 400 Pa, making this velocity range operationally justified for systems without induced-draft fans.

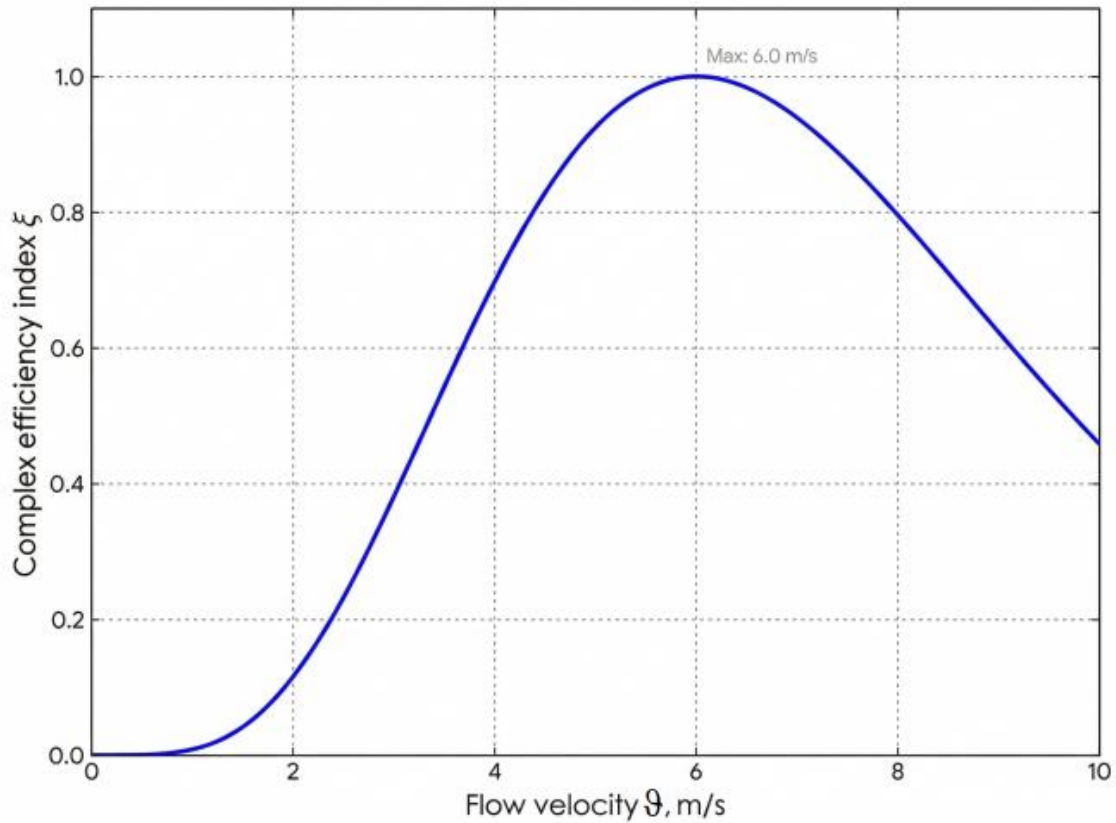


Fig. 4. Dependence of the energy efficiency indicator ξ on the gas flow velocity ϑ for equipment with a 0.9 m² cross-section.⁸

RESULTS AND DISCUSSION

Comparative Analysis of Energy Efficiency Indicators

The obtained numerical simulation results allow for a comparative analysis of the proposed solution with current international developments in the field of environmental modernization of energy facilities. In contrast to the works of Wang [7] and Mandi [8], where the main emphasis is placed on the general optimization of auxiliary cycles and heat recovery, this study proposes a radical reduction in auxiliary power consumption by modifying the aerodynamic flow structure. Traditional approaches considered in fundamental works on emission cleaning technologies [18] rely on classic high-resistance schemes (Venturi scrubbers, packed columns). In the proposed design, however, the use of macro-vortex structures enables a high degree of desulfurization (95.6–97%) at a resistance of only 400 Pa. This confirms the energy superiority of the developed

geometry over known global analogs for distributed generation systems. Based on the calculations, it was established that the total hydraulic resistance of the spiral channel in the optimized mode at 100% load (for a 2.6 MW power unit) is approximately 400 Pa. Notably, the dry aerodynamic resistance accounts for about 220–250 Pa, while additional losses due to friction and the generation of macro-vortex structures in the presence of irrigation amount to only 150–180 Pa. From the perspective of the GPPP energy balance, this signifies the virtual absence of any significant parasitic load on the engine exhaust system. According to research on the energy consumption analysis of gas cleaning systems [7], the optimization of auxiliary cycles significantly reduces the specific fuel consumption, which directly correlates with the economic sustainability of autonomous energy systems [8]. To ensure the reproducibility of the results, Table 3 presents the calculation environment parameters used in the numerical experiments.

⁸Appendix 1

Table 3⁹.

Parameters of the simulated gas flow (typical 2.6 MW GPPP)¹⁰.

Parameter	Value	Note
Inlet gas temperature, T	380 – 420 °C	GPPP exhaust at 100% load
Initial SO ₂ concentration	2200 mg/m ³	High-sulfur fuel (simulation)
Operating flow velocity, ϑ	3.8 – 7.7 m/s	Typical GPPP operating range
Dean number, De	10 ⁴ – 1.2·10 ⁵	Industrial macro-scale
Gas density, ρ	0.55 – 0.65 kg/m ³	At operating exhaust temperatures

Summarizing the analysis results, three characteristic strategies for operating the spiral-vortex system can be identified depending on the current load of the medium-capacity GPPP unit:

1. Energy-saving mode (50% load, $\vartheta \approx 3.8$ m/s): Characterized by minimal hydraulic resistance (less than 200 Pa). This mode is most appropriate when operating on low-sulfur fuel, where the priority is maximizing electricity savings for auxiliary needs.

2. Optimal balance mode (75% load, $\vartheta \approx 6.0$ m/s): Represents the "point of technical excellence" of the design (the peak of the ξ criterion). At this velocity, the macro-vortex structure achieves full stabilization, providing a high degree of absorption with moderate resistance. This mode is recommended as the primary setting for long-term operation.

3. Maximum intensity mode (100% load, $\vartheta \approx 7.7$ m/s): Provides the highest mass transfer coefficient due to maximum Dean numbers. Despite the resistance increasing to 400 Pa, this mode guarantees compliance with environmental standards even at peak concentrations of pollutants in the flue gases.

Mass Transfer Intensification Mechanism

In the spiral scrubber, the sulfur dioxide absorption process is limited by the diffusion resistance of the gas phase. According to the model [31], macrovortex structures significantly reduce the thickness of the diffusion boundary layer. Transverse circulation constantly refreshes the gas-liquid contact surface on the outer wall of the channel, where a stable absorbent film forms under the action of centrifugal forces. Furthermore, the versatility of the spiral-vortex geometry offers prospects for its adaptation to complex cleaning processes—not only for SO₂ but also for nitrogen oxides (NO_x), aligning with modern

trends in the development of combined gas cleaning systems [20].

The effective mass transfer rate constant in the spiral channel can be mathematically expressed through the Sherwood number (Sh):

$$Sh = 0.023 \cdot Re^{0.8} \cdot Sc^{1/3} \cdot (1 + 0.05 \cdot De^{0.5}) \quad (7)$$

where Sc is the Schmidt number. The factor $(1 + 0.05 \cdot De^{0.5})$ quantitatively describes the "energy bonus" provided by the spiral geometry: due to the generation of secondary flows, the mass transfer intensity increases proportionally to the square root of the Dean number [10, 14]. For GPPP conditions (high De values), this increase ensures effective cleaning even with a reduction in the unit's dimensions.

This allows for the use of more concentrated limestone slurries without the risk of system clogging, as the proposed equipment lacks packing. The application of such hydrodynamic effects is recognized as a critical factor in improving the efficiency of modern energy plants and reducing their environmental footprint [16]. The spiral geometry effectively acts as a "dynamic packing," operating solely on the kinetic energy of the engine's exhaust flow [11], which eliminates the need for additional intensification devices.

Practical Applicability in Distributed and Autonomous Energy

The implementation of the proposed design at existing distributed generation facilities (GPPPs) is economically justified by the absolute absence of moving parts, high operational resilience, and significantly lower maintenance costs compared to traditional scrubbing systems. According to the Total Cost of Ownership (TCO) methodology [32], the primary economic effect is achieved through direct electricity savings for the plant's

auxiliary needs in the long term, while simultaneously ensuring the stability of the cleaning process under fluctuating thermal loads. The validation of the selected calculation models is further supported by fundamental numerical studies of hydrodynamics in curvilinear channels [33], which also highlight the critical role of secondary flow structures and macro-vortex patterns in intensifying transport processes within the centrifugal force field. These findings are fully consistent with established engineering standards for energy management and the optimization of power system auxiliary loads [34]. Furthermore, the integration of such passive units aligns with the general theory of transport phenomena in complex multiphase flows and is supported by comprehensive feasibility analyses of advanced gas purification technologies and industrial environmental safety frameworks [35–37].

For facilities with a capacity of 2.6 MW and above, a modular configuration of spiral units is recommended. This ensures the stable operation of the separation system even with significant changes in engine load (from 50% to 100%), as the macro-vortex structure maintains its intensity and stability across a wide range of gas flow rates [26].

Such an approach enables regional energy enterprises and industrial hubs to effectively comply with tightening environmental regulations in the total absence of parasitic loads on the GPPP exhaust system. Eliminating additional induced-draft fans from the circuit not only reduces capital expenditures (CAPEX) but also enhances the overall fault tolerance of the power unit, transforming the gas cleaning system into a passive, self-regulating and reliable element of the modern technological chain.

CONCLUSIONS

In this study, a comprehensive investigation of the hydrodynamic characteristics of spiral-vortex scrubbers was conducted to enhance the energy efficiency of autonomous gas-piston power plants (GPPPs). Based on the numerical simulation and analytical review, the following conclusions were reached:

1. Macro-vortex intensification. It was established that the use of spiral channels with a cross-section of 0.9 m² enables the effective generation of stable macro-vortex structures. This ensures a consistently high degree of flue gas desulfurization (>95%) within the operating velocity range of 3.8–7.7 m/s, which fully corresponds to the

operating modes of modern 2.6–3.0 MW gas-piston units.

2. Aerodynamic superiority. The superiority of the proposed geometry over traditional Venturi units and packed columns was demonstrated. The total hydraulic resistance of the spiral channel in optimized mode is 400 Pa, which is 4–5 times lower than the maximum allowable backpressure limits for modern gas-piston engines. This pressure distribution allows for the complete elimination of auxiliary induced-draft fans from the process flow, reducing the station's auxiliary power consumption by 65–95 thousand kWh per year per power unit.

3. Parameter optimization. Based on multi-criteria analysis, it was determined that the optimal geometric parameter is the spiral inclination angle $\alpha=10^\circ$. The developed complex energy-ecological efficiency criterion ξ allowed for the identification of a working optimum point at velocities of 5.5–6.0 m/s, providing the best ratio between energy expenditure and cleaning quality while maintaining the macroscopic stability of the liquid film.

4. Mathematical verification. Mathematical justification using the Sherwood number showed that the "energy bonus" of the spiral geometry is directly proportional to the square root of the Dean number ($De^{0.5}$). The obtained dependencies can be utilized in the design and modernization of gas cleaning systems, providing a significant reduction in the specific fuel consumption for the auxiliary needs of energy enterprises.

Practical Application of Research Results

The calculated parameters and conclusions obtained during the study were verified using a reference 2.6 MW cogeneration unit (Jenbacher J616). The characteristics of this engine (flue gas flow rate of 25,000 m³/h at a temperature of 380–420 °C) confirmed the operability of the spiral-vortex equipment under real industrial conditions. The implementation of the system on this type of equipment ensures stable operation without induced-draft fans across the entire operating load range (50–100%), providing an economic effect by reducing the parasitic load on the engine by 8–12 kW.

APPENDIX 1

^{1,2}**Table 1.** Initial data and boundary conditions for numerical process simulation.

³**Fig. 1.** Algorithm for numerical simulation and optimization of scrubber parameters.

⁴**Fig. 2.** Innovative spiral-vortex apparatus: a) general layout; b) velocity distribution map in the channel

cross-section (visualization of secondary flow structures).

^{5,6}**Table 2.** Comparative indicators of gas cleaning systems (at $\vartheta=7.7$ m/s).

⁷**Fig. 3.** Dependence of the hydraulic resistance coefficient λ_s on the Dean number (De) in the macrovortex flow range.

⁸**Fig. 4.** Dependence of the energy efficiency indicator ξ on the gas flow velocity ϑ for equipment with a 0.9 m² cross-section.

^{9,10}**Table 3.** Parameters of the simulated gas flow (typical 2.6 MW GPPP).

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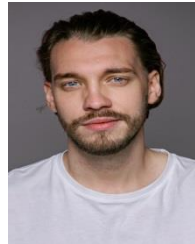
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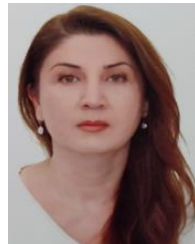
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