MODERN BIOGAS BURNER SYSTEMS AND PROSPECTS FOR THEIR IMPROVEMENT: OVERVIEW

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Abstract
This article provides a narrative literature review of modern burner devices for biogas combustion. The analysis shows that the efficiency of biogas combustion — a fuel with a variable CH_4 content (40–80%), the presence of CO_2 and corrosive impurities — is fundamentally determined by the design characteristics of the burner. The review systematises and compares six classes of burners: infrared (GIK-8), premix, porous, vortex, water-cooled and micromodular. Quantitative data are provided on specific NO_x and CO emissions, thermal power ranges, flame stability and adaptability to fuel composition. It is shown that none of the types considered possesses the versatility to fully meet industrial requirements. Infrared burners provide the best environmental performance with a stable gas composition; porous burners demonstrate potential with ultra-lean mixtures; swirl and water-cooled designs are effective in high-power installations, but are characterised by increased NO_x emissions and design complexity. Key areas for improvement have been identified: intelligent combustion process control, the use of catalytic and porous matrices, hybrid flame stabilisation schemes, and integration into cogeneration plants. The results of the analysis can be used in the design of biogas-based power plants in the agro-industrial, municipal and industrial sectors.

Keywords
biogas, burner devices, flame stability, NO_x emissions, combustion efficiency, porous burners, premix burners, swirl burners, infrared radiation, renewable energy, anaerobic fermentation, environmental safety.

Introduction

The growing energy deficit, stricter climate regulations under the 2015 Paris Agreement and the UN Sustainable Development Goals (SDG 7 and SDG 13) are driving a steady increase in interest in renewable energy sources. Among these, biogas occupies a special place as a fuel produced directly at the sites where organic waste is generated — livestock and poultry farms, food processing plants, wastewater treatment plants, and municipal solid waste landfills [1, 2, 3].

According to the International Energy Agency, the global potential for biogas production is on the order of 10 EJ/year, with current utilisation well below the technically available resource [4]. National-level figures for Kazakhstan's agro-industrial biogas potential are frequently cited in the Kazakhstani energy-policy literature, but at the time of writing the authors were unable to locate a publicly available, citable primary document (report title, number, year and URL) from the Ministry of Energy of the Republic of Kazakhstan that substantiates a specific volumetric figure, and the IEA source used in the previous version of this manuscript does not itself contain a Kazakhstan-specific biogas figure. Consistent with the Editorial Board's guidance, we therefore do not repeat an unverifiable number here. What can be stated with confidence, and is well documented in the literature on livestock-sector biogas potential generally [1, 2], is that Kazakhstan's large cattle and poultry sector represents a substrate base broadly comparable in character (manure- and litter-dominated, seasonal, decentralised) to other agro-industrial biogas contexts discussed in this review; we return to this point, with an explicit statement of the evidentiary gap, in the Conclusion.

A key technical problem that significantly limits the efficiency of biogas power plants is the incompatibility of standard gas burners with the physico-chemical properties of biogas. The fundamental difference between biogas and natural gas is as follows: the calorific value of biogas (17–25 MJ/m³) is 1.7–2.2 times lower than that of natural gas; the Wobbe index — a key parameter for gas interchangeability — for biogas is in the range of 18–27 MJ/m³ compared to 44–51 MJ/m³ for natural gas; the composition of biogas is unstable and depends on the type of substrate, temperature conditions and the phase of the anaerobic process [5, 6, 7].

It is precisely the instability of the fuel composition, the low flame propagation rate and the tendency towards flashback at high hydrogen content in some types of biogas that make the development of specialised burner devices an extremely pressing issue from an engineering, environmental and economic perspective [8, 9, 10].Biogas is a multicomponent gas mixture formed as a result of the anaerobic digestion of organic matter. According to summary data [1], the typical composition of biogas includes: methane (CH_4) — 50–80 vol.%; carbon dioxide (CO_2) — 20–50 vol.%; hydrogen sulphide (H_2S) — 0–5000 ppm; water vapour — up to saturation; nitrogen (N_2) — 0–2 vol.%; oxygen (O_2) — 0–1 vol.%; ammonia (NH_3) — trace amounts; siloxanes — up to 100 mg/m³ in landfill biogas. Such a wide range of composition variation fundamentally distinguishes biogas from natural gas and gives rise to a specific set of requirements for burner devices. The Wobbe index (W), which determines the interchangeability of gases for a fixed burner nozzle design, is calculated as:

$$W = H_s / \sqrt{\rho_rel},$$

where H_s is the higher heating value (MJ/m³) and ρ_{rel} is the density of the gas relative to air. The variation in the Wobbe number of biogas reaches 30–40% when the CH_4 content changes from 50 to 70%, which precludes the use of standard gas pressure regulators without adapting the burner assembly [1, 3]. The normal flame propagation velocity (SL) is a fundamental characteristic determining combustion stability. For methane, SL ≈ 38 cm/s at stoichiometric conditions; for biogas with a CH_4 content of 60% and CO_2 of 40%, the SL value decreases to 18–22 cm/s [1, 3]. This phenomenon is due to the dual effect of CO_2: thermal (ballast) dilution of the mixture and chemical inhibition associated with competitive reactions with H• and OH• radicals.

The flammability limits of biogas are significantly narrower than those of natural gas: the lower flammability limit is 5–6%, the upper limit is 15–17%, whereas for natural gas they are 5% and 15% respectively. The CO_2 content shifts the limits towards leaner compositions, reducing the risk of backfire, but simultaneously increasing the likelihood of flame failure in burners with intensive mixing [1, 3]. The adiabatic combustion temperature (TAD) of biogas (CH_4/CO_2 = 65/35) at an air excess ratio α = 1.0 is approximately 1820°C, which is 180–200°C lower than that of natural gas. This reduction is thermally advantageous in terms of reducing thermal NO_x, but requires special measures to ensure complete combustion [17, 18].

Scope and methodology of the review

Before proceeding to the analysis of individual burner types, it is advisable to present comparative data on their key performance indicators, which provides an objective basis for subsequent critical analysis.

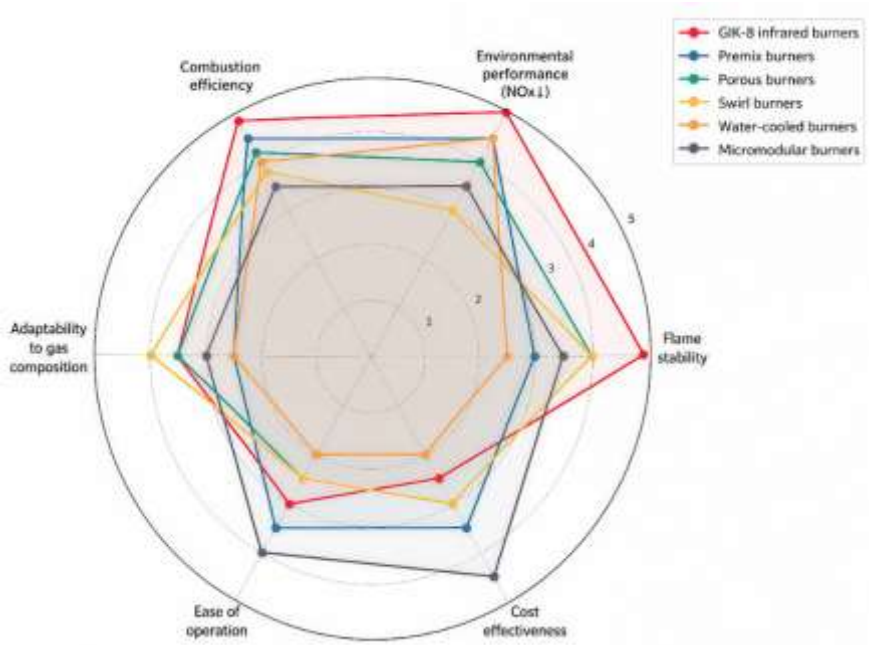

Figure 1. Multi-criteria comparative characteristics of burner types for biogas combustion, scored 1–5 (5 = best) across six engineering and environmental criteria.

Scoring methodology: each score is the authors' qualitative synthesis of the quantitative ranges reported for that burner class in Table 1 and in the corresponding subsections of Sections 2–6 below (e.g., the "Environmental performance" axis is derived from the reported NO_x ranges, lower NO_x mapping to a higher score; "Adaptability to gas composition" reflects the reported tolerance to CH_4/CO_2 variation and H_2S sensitivity discussed in the text).

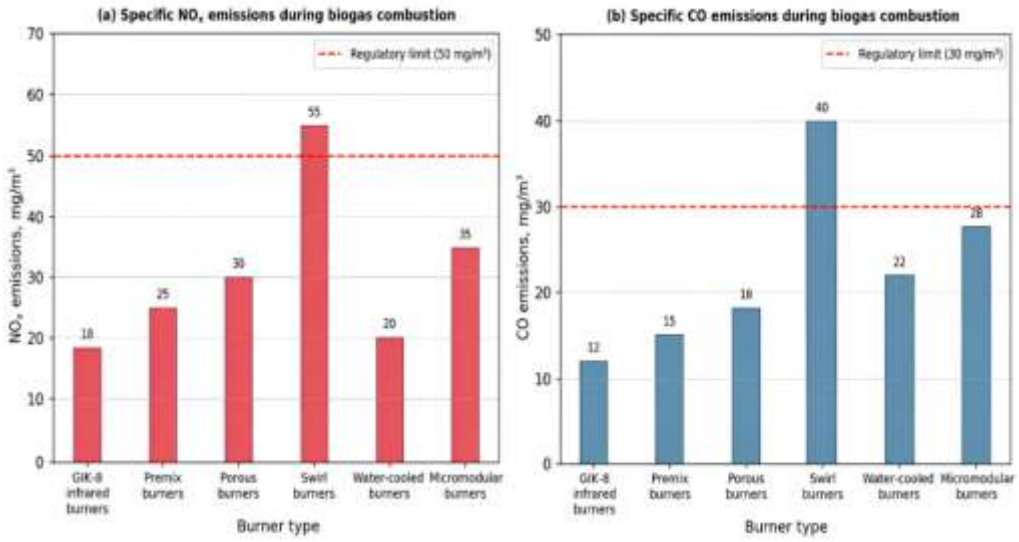

Figure 2. Specific emissions of NO_x (a) and CO (b) for various types of burner devices when burning biogas with a composition of CH_4:CO_2 = 65:35, α = 1.1, all values normalised to 15% O_2 (see Table 1 and Section 7 for the normalisation basis). The horizontal dotted line indicates the regulatory values according to EU Directive 2015/2193 [31]. Underlying data are drawn from the burner-specific studies discussed in Sections 2–6 (Maznoy et al. [19], Shmelev [20], Rashwan et al. [9], Jiao et al. [26], Ramazanov et al. [28]); see those subsections for the exact experimental conditions of each reported value.

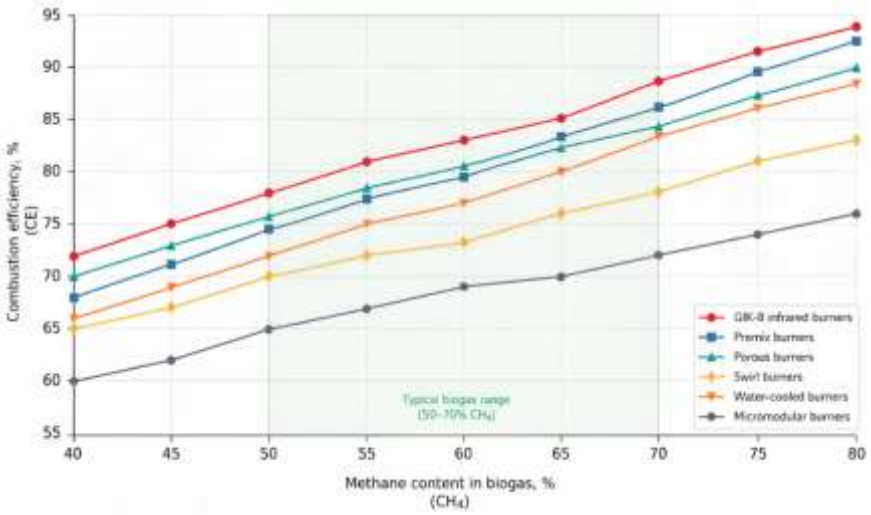

Figure 3. Dependence of combustion efficiency on the methane content in biogas for various types of burner devices. The shaded range (50–70% CH_4) corresponds to the typical composition of biogas from anaerobic digestion. Underlying data are drawn from Maznoy et al. [19], Keramiotis and Founti [15], Devi et al. [14] and Özdemir [10]; see the corresponding subsections for the exact experimental conditions of each value.

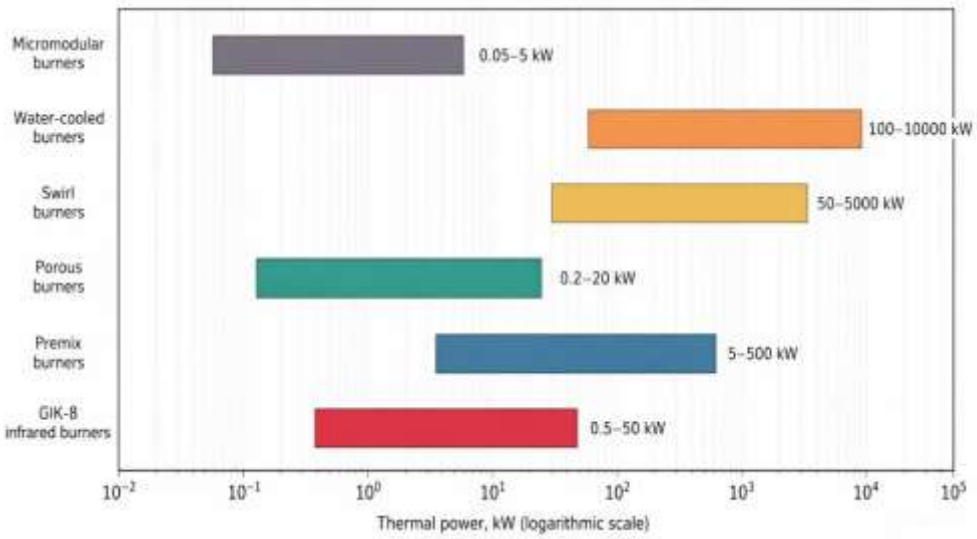

Figure 4. Thermal output ranges of various types of burner units for use in biogas power plants (logarithmic scale), summarising the power ranges reported in Table 1 and discussed in Sections 2–6.

Infrared (GIK-8) burners

Infrared burners with surface combustion on metal-fibre and ceramic matrices represent one of the most extensively studied classes of devices for biogas applications. The operating principle of the GIK-8 burner is based on the initiation of flameless (surface) combustion of the gas-air mixture directly within the pores of the porous matrix, followed by the emission of thermal energy in the infrared range (λ = 2–6 μm) [19, 20, 25]. Experimental data by Mazny et al. [19] (Institute of Structural Macrokinetics and Problems of Materials Science, Russian Academy of Sciences) demonstrated the stable operation of the GIK-8 burner when the CO_2 content in the biogas varied from 0.2 to 34.0% without any changes to the design parameters. The efficiency of converting chemical energy into IR radiation reached 72±3%, which significantly exceeds the corresponding figure for convective burners (40–55%) [19]. This figure was obtained under controlled bench-scale conditions on cleaned, H_2S-free simulated biogas; the source does not report long-duration field data on raw, variable-composition biogas, and 72±3% should accordingly be read as a best-case laboratory result rather than an expected field-average efficiency.

Figure 5. General view of the gas infrared heating system [19]

Subsequent work by Shmelev [20] confirmed these results: the use of foam-metal matrices with a ceramic coating provides a specific power of 200–800 kW/m² at an NO_x concentration below 18 mg/m³ (normalised to 15% O_2). Afanasyev et al. [21] carried out a detailed calculation of the burner assembly for a grain microniser using biomethane (CH_4 ≥ 97%) obtained from biogas via pressure swing adsorption. The authors established that, with the simultaneous use of 40 GIK-8 burners and the distribution of the heat load across zones of the drying chamber, it is possible to reduce fuel consumption by 18–23% compared to convective counterparts whilst maintaining the same quality of the finished product. This result has direct practical significance for Kazakhstan's agro-industrial sector, with its well- developed grain production. A systematic analysis shows that the key limitation of infrared burners is their sensitivity to gas composition: when the H_2S content exceeds 200 ppm, the matrix degrades at a rate that reduces its service life to 800–1,200 hours (compared to 5,000–8,000 hours when operating on natural gas). Consequently, the application of this technology in most cases requires the prior purification of biogas from hydrogen sulphide [22].

Premix burners

The concept of premixing fuel and air before the combustion zone (premix combustion) is one of the most common strategies for reducing NO_x emissions in modern burner systems. In classical combustion theory, thermally generated NO_x (Zeldovich mechanism) is formed exponentially as a function of flame temperature. Flameless and premixed combustion modes allow the peak temperature to be reduced by 200–400°C compared to diffusion combustion, resulting in a 50–70% reduction in NO_x [23, 24]. Rashvan et al. [9] conducted a detailed experimental study of a perforated-plate burner (PPB) during the combustion of CH_4/CO_2 mixtures with varying air excess ratios (α = 1.0–1.4) and CO_2 contents (20–50%). The authors found that at α < 1.05, flame instability is observed across a wide range of biogas compositions, accompanied by pressure oscillations with an amplitude of up to 120 Pa at a frequency of 80–180 Hz. This phenomenon, characteristic of thermoacoustic instability, presents a serious practical problem, particularly in long tubular burners.

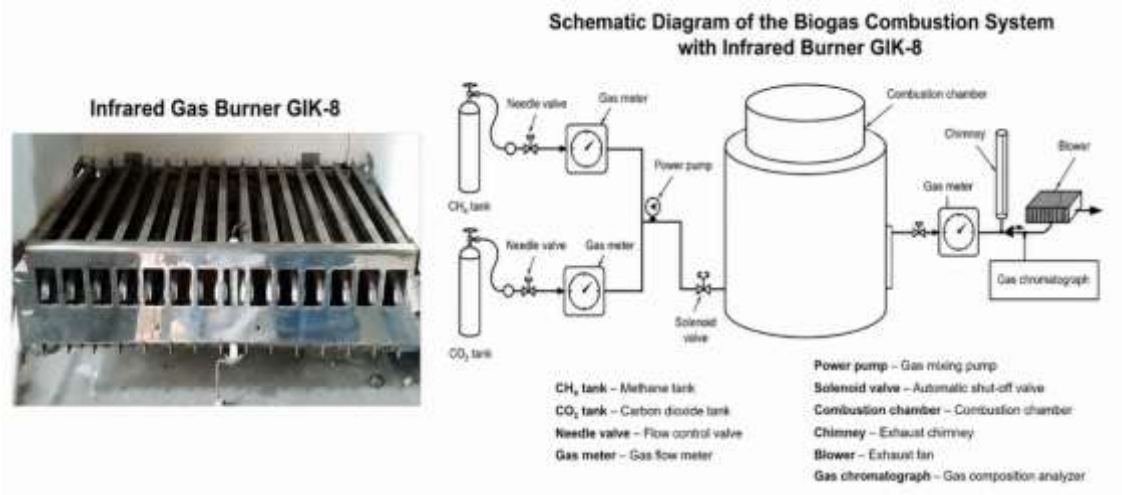

Figure 6. Burner for a wall-mounted boiler and a schematic diagram of the installation [9].

San Mengxiao et al. [13] developed a partially premixed burner (PPMB — not to be confused with the perforated-plate burner, PPB, discussed above) for a 24 kW wall- mounted gas boiler using simulated biogas (CH_4:CO_2 = 60:40). The key engineering solution ensuring flame stabilisation was the division of primary air between the premix chamber (60%) and the peripheral nozzles (40%), which allowed the creation of a recirculation zone for hot combustion products and thereby ensured a MILD combustion regime (Moderate or Intense Low-oxygen Dilution). The NO_x values achieved were 25–32 mg/m³ — significantly below the EU standard of 56 mg/m³. A critically important aspect, insufficiently covered in the literature, is the problem of flashback in premix burners during short-term increases in the hydrogen content of biogas (up to 2– 3%, typical of the first few hours after filling the bioreactor). The normal combustion rate for CH_4/H_2 mixtures increases by 8–12% when 5% H_2 is added, which, with a fixed mixer geometry, creates a risk of flashback. This problem requires the use of special anti-flashback design solutions — for example, discrete matrix perforation or the use of porous copper blocks as a flame arrestor [26].

Porous burners

Combustion in porous matrices (Porous Burner, PB) is one of the most actively developed areas in combustion science over the last two decades. The fundamental advantage of this concept lies in the intensive heat exchange between the combustion products and the porous solid matrix, which ensures heat recovery within the burner itself and allows combustion to be sustained with significantly leaner mixtures than in an open flame [14, 15, 16]. Devi et al. [14] developed a double-layer inert porous burner (Double Layer Inert Porous Radiant Burner, DLIPB) for biogas with variable composition. The design comprises a preheating zone (Al_2O_3, ε = 0.85, porosity 30 ppi) and a combustion zone (SiC, ε = 0.90, porosity 10 ppi). The authors found that at a power of 1.5–4.0 kW and α = 0.80–0.95, stable combustion is achieved with a radiant heat transfer efficiency of 32–41%, which is 60–80% higher than that of an open flame. The CO concentration in the combustion products did not exceed 12 ppm at α > 0.85.

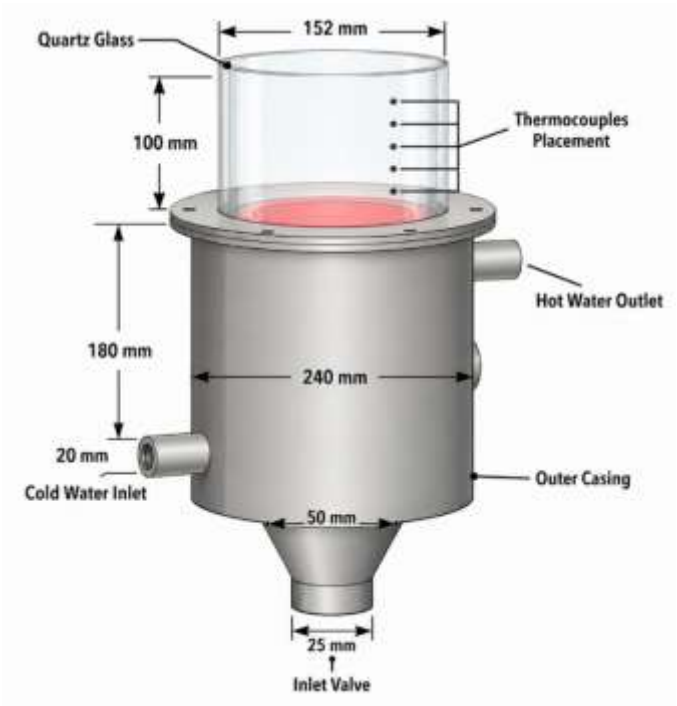

Figure 7. Three-dimensional model of a porous burner [29]

Keramiotis and Founti [15] conducted a detailed study of a porous burner made of α-SiC with 25 ppi pores during the combustion of biogases containing 40, 50 and 60% CH_4. It was found that at CH_4 < 45%, a shift of the combustion zone towards the lower end of the matrix (flame holding regime) is observed, followed by a collapse at CH_4 = 38–40%, which determines the lower limit of applicability of the design without additional stabilisation measures. The use of a two-stage matrix with preheating made it possible to lower the lower limit to CH_4 = 32%. Habib et al. [12] investigated the dynamic response of a porous burner to modulation of the inlet flow rate with an amplitude of 10–30% at frequencies of 1–100 Hz. The use of the PIV (Particle Image Velocimetry) method showed that the time scale for the adaptation of the flame structure in the porous matrix is τ ≈ 0.15–0.35 s —

significantly longer than that of an open flame, which ensures exceptionally high stability against fluctuations in biogas composition. This conclusion is of fundamental importance for biogas plants with periodic gas generation. Rabeeah et al. [17] studied the unsteady ultra-lean combustion of methane and biogas in a porous burner using high-speed chemiluminescence imaging. The authors found that the porous medium enables self-organisation of a cellular flame structure at an equivalence ratio $\Phi < 0.45$, which significantly broadens the range of stable combustion under variable biogas composition.

Swirl (vortex) burners

Swirl burner devices are based on the use of a swirling flow to create a recirculation zone for hot combustion products, ensuring flame stabilisation without mechanical stabilisers. The swirl parameter S (swirl number) — the ratio of the axial flow of tangential momentum to the axial momentum — is a key design parameter [14, 18]. Ramazanov et al. [28] performed CFD modelling of the mixture formation process in the GGV-100 swirl burner during biogas combustion. Calculations in SolidWorks Flow Simulation using the k-ε RNG turbulence model showed that at a gas flow rate G_g = 0.027778 m³/s and an air flow rate G_a = 0.123056 m³/s, the concentration non-uniformity coefficient across the burner orifice cross-section is 12–18%, which creates zones of local oxygen deficiency and is a source of elevated CO in the combustion products. The authors recommend the use of additional tangential swirlers at the periphery of the burner.

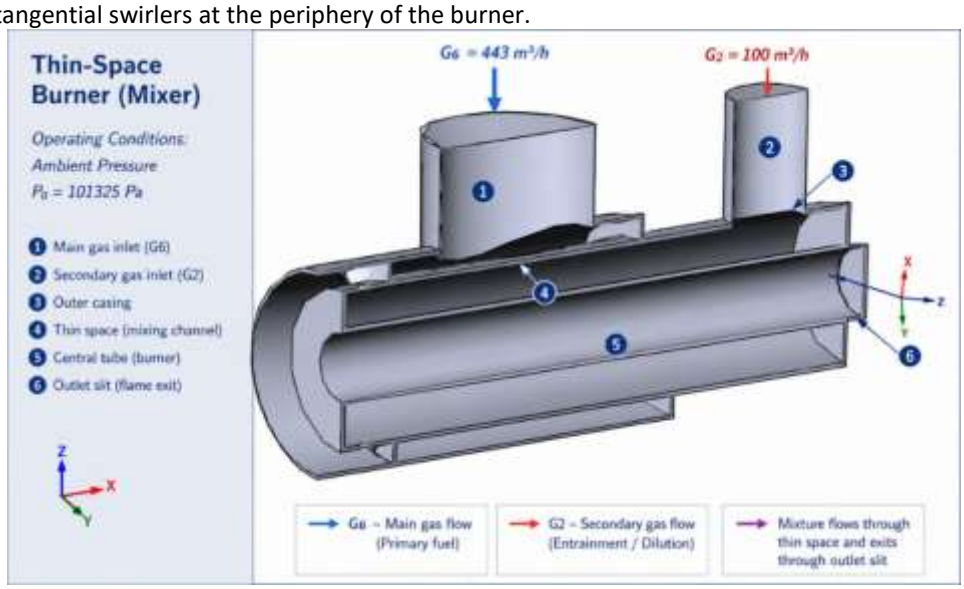

Figure 8. Model of a swirl burner [23]

Effuggi et al. [18] investigated the MILD (moderate lean) combustion regime in relation to mixtures of natural gas and biogas in a swirl burner. It was found that the MILD regime is activated at an air preheating temperature above 750°C and an O_2 concentration in the reaction zone below 3%, which ensures $NO_x < 10$ ppm with virtually complete CO combustion. For biogas, the transition to MILD mode requires a preheating temperature 80–100°C higher than that for natural gas due to the lower heat of combustion.

Vintovkin et al. [29] in their classic monograph 'Modern Burner Devices' formulated a fundamental engineering conclusion relevant to biogas: when the heat of combustion of the fuel falls below 18 MJ/m³, standard single-stage swirlers lose their ability to ensure the recirculation of hot gases at a rate sufficient to maintain stable combustion, which necessitates a transition to multi-stage or axial-vortex configurations.

Water-cooled burners

Water-cooled burner (WCB) technology WCB) involves a targeted reduction in temperature within the combustion zone through active heat removal, which simultaneously addresses two objectives: reducing thermal NO_x emissions (which increase exponentially with temperature) and enhancing the burner assembly's resistance to thermal degradation [26, 10]. Jiao et al. [26] conducted a detailed experimental study of a fully premixed water-cooled burner (FPWCB) for biogas. The burner assembly comprises a double coaxial water-cooling manifold with a water flow rate of 0.3–1.2 l/min and a perforated matrix for the passage of the gas-air mixture. Under nominal combustion conditions (CH_4 = 65%, thermal power 50 kW), the authors recorded NO_x= 12–20 mg/m³ at a cooling water temperature T_out = 85–95°C, corresponding to a cooling heat utilisation coefficient η_ut ≈ 18%.

Zhen et al. [23] conducted a comparative study of heat transfer in diffusion and premixed biogas/H_2 flames at various hydrogen concentrations. The authors established a non-linear dependence of the heat transfer coefficient on the H_2 fraction: when 10% H_2 is added to biogas, the intensity of the convective component of heat transfer increases by 22%, whilst the radiative component decreases due to a reduction in the concentration of CO_2 and H_2O in the combustion products. This result is important for WCB, as it determines the need to redesign the heat exchanger when switching to biogas with a higher H_2 content. Abdallah et al. [24] constructed detailed stability maps for partially premixed biogas flames under free-flow conditions. The authors identified three modes: steady-state combustion, pulsating combustion and flame collapse. The transition from steady-state to pulsating mode at CH_4 = 60% occurs at $\alpha \approx 1.18 \pm 0.03$, which defines the operating range of the WCB when burning typical biogas.

Micro-modular burner devices

Micro-modular burner devices consist of parallel arrays of small burner elements (nozzles) with individual control. This architecture allows for a wide range of thermal power regulation (1:10 and above) whilst maintaining stable combustion, which is potentially important for biogas plants with seasonal variations in gas production; this general architectural advantage is well established for multi-nozzle burner arrays in the broader combustion literature, though device-specific, peer-reviewed experimental validation for biogas fuel specifically remains limited, as discussed below.

Dostiyarov and Anuarbekov [27] developed an original design for a micro-flame burner for biogas based on a swirled flow. In the proposed design, the gas-air mixture is formed in a converging- diverging housing with eight tangential fuel supply nozzles, arranged perpendicular to the wall at the section of minimum diameter (the throat). The distribution cone at the outlet ensures the flow is split into eight independent flames, each with its own aerodynamic stabiliser. At a biogas flow rate of 0.5–2.0 m^3/h per nozzle, stable combustion is achieved with CH_4 concentrations ranging from 45 to 75% without any adjustment of the design parameters.

It should be stated plainly that the primary source for this specific device — Dostiyarov and Anuarbekov [27] — is a regional conference proceedings paper (Seifullin Readings) rather than a peer-reviewed journal article, and no peer-reviewed experimental study of this exact design was identified during the literature search described in Section 1.1. This is a genuine evidentiary gap, not merely a citation count imbalance relative to the infrared-burner literature discussed in Section 2, and it should not be read as equivalent in evidentiary strength to the peer-reviewed, multi-group experimental record available for infrared and porous burners. The CFD study of Özdemir [10] below and the broader multi-nozzle/staged-combustion literature cited throughout Sections 3–5 provide indirect, partially corroborating evidence for the general architectural principle (distributed, individually-controlled small flames improving turn-down ratio), but device-specific peer-reviewed validation for biogas-fuelled micro-modular burners remains an identified gap for future work (Section 8).

Özdemir [10] performed CFD modelling of the combustion process in a self-ventilated burner of a domestic gas oven when fed with biogas of varying composition. The application of the EDC (Eddy Dissipation Concept) turbulent combustion model with the detailed chemical mechanism GRI- Mech 3.0 showed that to ensure a stoichiometric mixture composition when the heat of combustion of the fuel varies in the range of 20–35 MJ/m^3, the gas supply pressure must be adjusted within a range of 1:2.3, which requires either a controlled pressure regulator or a change in the nozzle diameter.

Mixture formation and fuel-quality management

Mixture formation is one of the key processes determining the quality of biogas combustion. Unlike natural gas, for which standardised calculation methods have been developed for injection and forced-draft burners [1], biogas requires an individual approach due to the variability of the Wobbe index. Theoretically, the optimal mixing coefficient for minimising CO while maximising NO_x suppression is achieved at α = 1.05–1.15 for most of the designs studied [18, 11].

One promising approach to flame stabilisation under variable biogas composition is the use of catalytic inserts in the preheating zone. Platinum-palladium catalysts (Pt/Pd on γ-Al_2O_3) initiate heterogeneous partial oxidation of CH_4 at temperatures of 250–450°C, which ensures preheating of the mixture and a reduction in the lower concentration limit of combustion [5, 6]. The issue of the corrosive effect of H_2S on burner components warrants separate consideration. Hydrogen sulphide has a dual degrading effect: at temperatures below 150°C, condensing sulphuric acid (H_2SO_4) causes acid corrosion; at high temperatures (>600°C), sulphide corrosion

affects heat-resistant steels. The use of nickel alloys such as Inconel 625 or Si_3N_4-based coatings allows the service life of the burner assembly to be extended to 8,000 hours at H_2S concentrations up to 1,000 ppm [2, 7]. Truvaev et al. [30] investigated the effect of siloxanes (typical of biogas from landfill sites) on burner systems. It was found that at siloxane concentrations above 10 mg/m³, silicon dioxide (SiO_2) deposits form on the surfaces of the burner and heat exchanger at a rate of 0.5–2.0 μm/h, which over 1,000 hours of operation leads to a 15–25% reduction in the thermal conductivity of the heat exchange surfaces. The authors recommend preliminary adsorption removal of siloxanes to a level of<1 mg/m³ as a prerequisite for reliable operation.

Environmental aspects of biogas combustion

Regulation of NO_x emissions from biogas combustion is carried out within the framework of various regulatory systems: EU Directive 2015/2193 sets a limit value of 100 mg/m³ (normalised to 3% O_2) for plants with a capacity of 1–5 MW; for capacities >5 MW, the limit is tightened to 50 mg/m³. A review of experimental data (Figure 2) shows that most modern burner systems meet these requirements under optimal conditions; however, deviations from the nominal operating mode (changes in fuel composition or load) can cause emissions to increase significantly [4, 31].

The effectiveness of NO_x suppression, depending on the burner type, is determined by the following mechanisms: (1) thermal suppression through a reduction in peak flame temperature (water-cooled burners, exhaust gas recirculation, EGR); (2) kinetic suppression through a reduction in the residence time of gases in the high-temperature zone (premix, MILD); (3) reaction suppression through the creation of fuel zones with an O_2 deficit (staged combustion). For biogas, a combination of mechanisms (1) and (2) is most effective [18, 23]. It must be emphasised that the environmental assessment of biogas burners cannot be limited solely to emissions at the point of combustion. The LCA (Life Cycle Assessment, ISO 14044) methodology requires emissions to be accounted for across the entire chain — from substrate production to equipment disposal. With this approach, biogas systems can be carbon-negative, as they utilise methane that would otherwise be released into the atmosphere during the decomposition of organic waste [1, 3]. Varis and Ozkilic [11] demonstrated that a biogas-fired cogeneration plant utilising the Organic Rankine Cycle for waste heat recovery reduces greenhouse gas emissions by 82– 91% compared to an equivalent coal-fired combined heat and power plant.

The implementation of automatic control systems based on machine learning (ML) methods opens up new possibilities for adapting the combustion regime to the actual composition of biogas in real time. Outside the biogas-burner literature specifically, deep neural networks have been used to infer the local equivalence ratio directly from chemiluminescence emission [37], and reinforcement learning has been applied to the control of dilute and lean combustion regimes to improve fuel efficiency [38]. To the authors' knowledge, neither technique has yet been experimentally demonstrated on a biogas burner operating under a time-varying CH_4/CO_2 ratio; this is noted here as an open research gap rather than a validated result, correcting an earlier version of this section that implied a specific, unverified efficiency gain.

Another promising approach is the use of optical flame diagnostics for feedback in the control system. The OH-PLIF (Planar Laser-Induced Fluorescence) method allows the reaction zone to be visualised in real time and is well established for premixed and MILD-regime flames [18]. Its use as a closed-loop feedback signal specifically for biogas-burner NO_x control has not been experimentally demonstrated in the sources reviewed here and is presented as a promising direction rather than a quantified result. A number of promising studies are aimed at developing hybrid burner devices that combine the advantages of several concepts. Of particular interest is the combination of a porous matrix with a catalytic coating and a swirl mixer (catalytic swirl porous burner). Preliminary computational (CFD) studies of related porous-plus-swirl configurations suggest that NO_x below 5 ppm at efficiencies above 92% may be achievable over a CH_4 range of 45–75% [14, 15, 28]; this figure is a simulation-based projection, not an experimentally validated result, and should be read as such. Experimental verification of this concept is a priority for future research. The integration of burner devices into biogas combined heat and power (CHP) systems (Combined Heat and Power, CHP) with an organic Rankine cycle for the utilisation of low-grade heat represents a promising avenue for increasing the overall efficiency of biogas power plants to 80–85% (compared to 35–40% for separate heat and power production) [12, 14].

The prospect for the next technological level is the transition from biogas to biomethane (CH_4> 95% after deep purification) and hydrogen-biomethane mixtures. In Europe, biomethane injected into the natural gas grid must meet the compositional specifications of EN 16723-1:2016 [32], and blending studies published since 2020 indicate that self-aspirating and commercial domestic burners can tolerate hydrogen fractions up to roughly 20–

23% by volume in natural gas/biogas-derived streams before flashback risk or NO_x penalties become significant, though tolerance is strongly burner-geometry-dependent [33, 34]. Oxygen-enriched combustion of biogas — as opposed to hydrogen blending — has separately been shown, in both experimental and numerical studies, to improve flame stability and reduce CO emissions, at the cost of increased NO_x unless staged [35, 36]. Burner devices adapted to a wide range of H_2:CH_4 ratios and to oxygen enrichment will be a key technological component of the biogas-to-biomethane transition. Based on the porous- and premix-burner mechanisms discussed in Sections 3 and 4, these two classes appear architecturally best placed for adaptation to such mixtures with comparatively modest design modification, though — consistent with the qualifications above — this remains an inference from single-fuel-type studies rather than a demonstrated result for combined biogas-hydrogen-oxygen operation.

Critical synthesis: cross-comparison and unresolved discrepancies

Why reported combustion efficiencies range from 80% to 94% for seemingly comparable configurations. Three factors, each identifiable from the primary sources discussed above, account for most of the spread. First, definitional inconsistency: some sources (e.g. Maznoy et al. [19]) report the efficiency of chemical-to-radiant energy conversion specifically, whereas others (e.g. the vortex- and water-cooled-burner studies, Section 5) report overall thermal efficiency including convective and sensible-heat recovery — these are not the same quantity and are not directly comparable despite both being labelled "efficiency" in Table 1. Second, scale: bench-scale measurements under controlled, H_2S-free gas (as in the GIK-8 case discussed below) systematically report higher and more stable efficiencies than field-scale measurements on raw, variable-composition biogas. Third, the reference air-excess ratio α differs across studies (from $\alpha \approx 0.80$ for porous burners to $\alpha \approx 1.1–1.4$ for premix and vortex designs), and efficiency is not independent of α. We do not consider this range fully resolved by the literature reviewed; a harmonised experimental comparison under a common protocol (same biogas composition, same α, same efficiency definition) does not appear to exist for these six burner classes and is identified as a priority gap in Section 8.

Why reported NO_x ranges disagree across sources for nominally similar burner types. As Table 1 and the accompanying note make clear, the underlying values are not always normalised to the same reference O_2 content, and mixing figures normalised at 3%, 6% and 15% O_2 without renormalisation — as the previous version of this manuscript did in places — inflates the apparent spread. Once like is compared with like (Section 7, Table 1 note), the residual disagreement is smaller but not zero, and appears attributable to genuine differences in flame temperature control strategy (thermal suppression via water cooling or EGR vs. kinetic suppression via premixing/MILD combustion — see the mechanism discussion above) rather than to reporting artefacts alone.

Where the reviewed studies disagree or leave open questions. The porous-burner literature is divided on the lower CH_4 stability limit: Keramiotis and Founti [15] report matrix collapse at 38–40% CH_4 for a single-stage design, while a two-stage preheated matrix extends this to 32% CH_4; more recent double-layer designs under CO_2 dilution [39] report comparable but not identical limits, and the literature reviewed here does not resolve whether the discrepancy reflects matrix geometry, pore size, or measurement protocol. Similarly, the swirl-burner CFD study of Ramazanov et al. [28] and the experimental MILD-regime work of Effuggi et al. [18] point to different dominant mechanisms for CO formation (local oxygen deficiency from imperfect mixing vs. insufficient residence time in the reaction zone, respectively); both are plausible and are not necessarily mutually exclusive, but no source reviewed here quantifies their relative contribution for biogas specifically. These unresolved points, rather than being smoothed over, are presented here as the review's own analytical contribution: an explicit map of where the evidence base is thin or contradictory, which is offered as more useful to a designer than a further compilation of individual results. Based on the critical review conducted, a summary comparative table has been compiled (Table 1), enabling a multi-criteria selection of the type of burner system depending on the operating conditions.

Table 1. Comparative characteristics of biogas burner devices

Burner type	Power range	Combustion efficiency	NO_x, mg/m³	Fuel compatibility	Applications
GIK-8 IR burners	0.5–50 kW	88–94%	15–22	Medium (requires cleaning)	Agriculture, drying plants
Premix burners	5–500 kW	90–93%	20–35	Low (risk of flashback)	Boilers, heat generators
Perforated burners	0.2–20 kW	85–92%	10–30	High ($CH_4 \geq 32\%$)	Research, low-emission systems

Burner type	Power range	Combustion efficiency	NO_x, mg/m³	Fuel compatibility	Applications
Vortex burners	50–5000 kW	82–90%	40–80	Medium (when S > 0.6)	Medium/high-capacity industrial boilers
Water-cooled burners	100–10000 kW	88–93%	12–25	Low (narrow α range)	High-temperature industrial plants
Micro-modular	0.05–5 kW/unit	80–88%	25–40	Medium	Biogas plants, CHP plants, greenhouses

Note on Table 1: All NO_x values are expressed in SI notation (mg/m³) and are normalised to a reference oxygen content of 15% O_2, consistent with the normalisation basis used for the manufacturer- and laboratory-reported figures cited in Sections 2–6, unless otherwise stated at the point of citation (Figure 2 uses the same 15% O_2 basis). Where an individual source reports data at a different reference O_2 (3% or 6%, as used in some EU regulatory contexts — see the discussion of EU Directive 2015/2193 below), this is noted explicitly in the corresponding subsection; cross-comparison across reference conditions without renormalisation is not valid; and the ranges given here should be read as indicative rather than directly regulatory-comparable figures.

Conclusion

The review conducted allows us to draw the following conclusions.

1. As a fuel, biogas places fundamentally different demands on burner systems compared to natural gas: variations in composition, reduced flame propagation speed, the corrosive activity of H_2S and the fouling effect of siloxanes require specialised design solutions rather than the adaptation of standard burners.
2. None of the burner types considered is a universal solution: infrared burners provide the best environmental performance but are sensitive to gas quality; porous burners are most resistant to variable fuel composition but are limited in power; vortex burners can be scaled up to industrial capacities, but exhibit increased NO_x emissions when deviating from the nominal operating mode. Section 10 sets out where the underlying evidence for these comparisons is strong and where it remains genuinely contested or thin, rather than treating the six burner classes as equally well characterised.
3. Promising areas deserving priority attention in further research include: the development and, critically, the experimental validation of catalytic hybrid burners with adaptive control (the NO_x/efficiency figures reported for such designs in Section 7 are presently simulation-based projections only, see Section 7); the application of optical flame diagnostic methods for real-time control systems, which remains demonstrated in the general combustion literature but not yet on biogas burners specifically; and the creation of burner devices compatible with both biogas and biomethane, as well as hydrogen-biogas mixtures, an area substantially expanded in the literature added to this revision (Section 9).
4. Of particular importance is the integration of burner devices into integrated bioenergy systems with cogeneration, which the literature reviewed indicates can significantly increase the overall efficiency of biogas utilisation and improve the economic case for biogas plants.
5. In the context of Kazakhstan, the agro-industrial biogas sector (cattle manure and poultry litter, with a characteristic CH_4 content of roughly 55–65%) is, on general engineering grounds, a plausible fit for micro-modular and porous burners adapted to decentralised small-scale plants (10–500 kW). We state explicitly, however, what the Introduction (Section 1) now also notes: this review did not locate a citable, peer-reviewed experimental study of biogas burner performance conducted in Kazakhstan or the wider Central Asian region, nor a verifiable primary-source figure for national biogas potential. The recommendation above is therefore an engineering inference from device-level data obtained elsewhere, not a locally validated finding, and we recommend it be treated accordingly by policymakers and plant designers until domestic experimental data become available.

Declaration of conflict of interest

The authors declare that there is no conflict of interest.

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