

Automation of a Pneumatic Substrate Mixing System in a Biogas Plant

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Keywords: Biogas Plant, Anaerobic Digestion, Pneumatic Mixing, Barbotage, Intermittent Mixing, Automation, Solenoid Valve, Time Relay, Duty Cycle, Small-Scale Biogas Systems.

Abstract: Effective substrate mixing is a critical factor in the stable operation of anaerobic digesters, directly influencing mass transfer, temperature distribution, and overall biogas productivity. This paper reviews the engineering principles and practical implementation of pneumatic (barbotage) mixing in biogas reactors, with emphasis on intermittent operation controlled by standard industrial automation components. The system utilizes internally produced biogas as the working medium for cyclic gas injection, eliminating the need for mechanical agitators. The paper formalizes the duty-cycle concept for intermittent barbotage through two timing parameters - valve opening time (T_{on}) and pause duration (T_{off}) - and discusses their practical selection based on reactor geometry, substrate rheology, and operational requirements. A structured comparison of manual and automated mixing modes is presented, highlighting the limitations of operator-dependent control and the engineering advantages of timer-based actuation. The reviewed literature consistently indicates that intermittent gas mixing reduces energy demand while maintaining acceptable substrate homogeneity in small and medium-scale anaerobic digesters. The described approach demonstrates that low-cost automation based on a time relay and a solenoid valve can substantially improve operational repeatability in small-scale biogas installations without requiring complex programmable control systems. Practical timing guidelines and component specifications are provided to support engineering implementation.

1 INTRODUCTION

Biogas plants are widely used for the conversion of organic wastes into biogas and digestate that can be utilized as fertilizer [1], [2]. A key unit of a biogas plant is the anaerobic reactor, where methane fermentation occurs. To maintain favorable conditions for methanogenic microorganisms and to mitigate medium non-uniformity, the substrate in the reactor must be mixed. Among available mixing strategies, pneumatic (barbotage) mixing by biogas jets offers a mechanically simple alternative to conventional impeller-based agitation. The biogas generated during anaerobic digestion is supplied to a gas distribution system and used as the driving medium for mixing. This approach enables substrate agitation without a mechanical agitator and can improve process stability by maintaining more homogeneous conditions in the reactor [3]. A major

drawback of manual mixing control is its dependence on the operator: both the switching frequency and the duration of gas supply may deviate from the intended schedule, thereby reducing the repeatability of the operating regime [4]. To eliminate the human factor, an automatic mode based on a solenoid valve actuated by a time relay according to a predefined program is considered a practical and cost-effective solution [5]. The objective of this paper is to review the system configuration and the control principles that enable automated barbotage mixing in small-scale biogas plants. In contrast to general descriptions of gas mixing in digesters, this work provides a structured engineering description of intermittent pneumatic mixing as a timer-controlled duty-cycle process. The main contribution is the formalization of duty-cycle parameters (T_{on} and T_{off}) and the practical control sequence enabling repeatable cyclic barbotage operation using standard industrial components. This

makes it possible to compare operating modes, identify the engineering benefits of automation, and define practical timing parameters for small-scale biogas plants without using complex programmable control systems [6].

2 BACKGROUND AND ANALYSIS OF MIXING APPROACHES

Mixing in anaerobic reactors is commonly regarded as an essential operation that affects the spatial distribution of temperature, substrate concentration, microbial populations, and overall mass-transfer conditions. Insufficient mixing may lead to stratification, local accumulation of solids, and the formation of zones with different physicochemical conditions, which can negatively influence process stability. Conversely, excessive mixing intensity may increase energy demand and may adversely affect the anaerobic microbial consortia, particularly when the hydrodynamic shear becomes significant. Therefore, the selection of a mixing strategy remains an important engineering task and is widely discussed in the literature, especially in the context of balancing process stability and energy efficiency [2], [3].

Several studies have emphasized that mixing performance should not be interpreted solely in terms of achieving complete homogeneity. In practical anaerobic digestion systems, the purpose of mixing is often to provide sufficient contact between microorganisms and substrate, to improve heat distribution, and to prevent the formation of stagnant zones, while avoiding unnecessary energy consumption. Consequently, researchers consider the choice between continuous and intermittent mixing regimes and propose that intermittent operation can be advantageous, particularly for full-scale plants where mixing accounts for a noticeable portion of total auxiliary power consumption [2], [3].

A number of publications indicate that intermittent mixing can serve as an effective alternative to continuous mixing. By providing periodic “on/off” operation, intermittent regimes may ensure acceptable homogeneity at reduced energy consumption and allow the optimization of mixing duty cycles depending on digester loading and operating conditions [4] - [6]. In addition, the intermittent approach provides a technical basis for automation, since the mixing program can be explicitly expressed through time parameters defining the activation duration and the pause

interval. This feature is important for real plants, where operational simplicity and reproducibility of control actions are essential for stable long-term operation.

Recent review papers underline that the mixing strategy is determined not only by hydrodynamics but also by the overall energy balance of the plant, equipment configuration, maintenance requirements, and operating expenditures [2], [3], [7] - [9]. For this reason, an “optimal” mixing strategy is not universal: it is influenced by reactor geometry, substrate rheology, the presence of gas-liquid-solid phases, and the constraints of the available mixing equipment. Accordingly, there is continuous interest in alternative mixing concepts that reduce mechanical complexity and enable reliable control of the mixing regime under industrial conditions.

Barbotage (gas mixing) is commonly defined as the motion of a multitude of gas bubbles through a liquid medium [10]. In anaerobic digestion systems, gas-driven mixing is attractive because it may eliminate the need for mechanical agitators and may utilize part of the produced biogas to generate the mixing flow. From an engineering perspective, this approach shifts the primary challenges from mechanical design to the design of the gas line, distribution elements, and control devices that ensure stable and repeatable biogas delivery to spargers.

Based on the above considerations, gas-driven (barbotage) mixing combined with intermittent operation appears to be a promising approach for anaerobic reactors, as it reduces mechanical complexity while enabling flexible timing control. In this context, the implementation of an automatic control algorithm for biogas supply becomes crucial for achieving repeatable operating regimes and minimizing operator influence. Therefore, the following section describes the configuration of the proposed pneumatic mixing system and its key functional elements, which form the basis for automated cyclic barbotage mixing in a biogas plant.

3 DESCRIPTION OF THE PNEUMATIC MIXING SYSTEM

The pneumatic mixing system utilizes the biogas released during anaerobic digestion as the working medium for substrate agitation. During normal operation, biogas accumulates in the reactor headspace at relatively low pressure. A compressor withdraws the biogas from the headspace and directs it through the gas line. The gas then passes through a

water seal, which serves as a protective element of the pneumatic circuit, and enters a receiver, where it is accumulated under pressure. Subsequently, the biogas is supplied to the collector inlet chamber and distributed through pipelines to the spargers installed in the reactor (Fig. 1). This configuration enables the use of internally generated biogas as an energy carrier for mixing, thereby reducing the need for mechanical agitation devices.

The spargers are equipped with perforated nozzles. During operation, biogas jets pass through the perforations, rise through the substrate volume, and form a gas-liquid flow structure that promotes mixing. This mechanism facilitates redistribution of the substrate and contributes to mitigating stagnant zones within the reactor. A cross-shaped sparger configuration is known to provide more uniform spatial distribution of gas jets over the reactor working area, preventing void formation and local thermal gradients [3] (Fig. 2).

The control arrangement includes two valves integrated into the biogas supply line: a shut-off valve and a solenoid valve. In the manual mode, the solenoid valve remains closed, and the operator periodically opens and closes the shut-off valve, thereby controlling the mixing cycles. In the automatic mode, the shut-off valve is closed, and the solenoid valve is opened and closed according to commands from a time relay in accordance with a predefined program. Such an approach enables barbotage mixing without a mechanical agitator and provides regular cyclic operation with a specified time interval, improving repeatability of the mixing regime and reducing operator dependency.

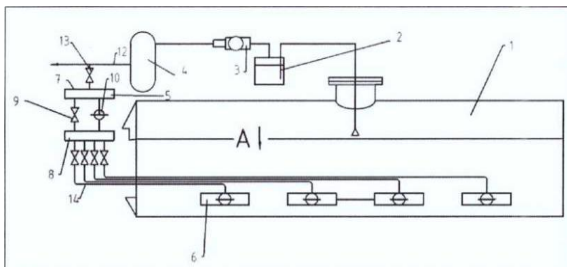


Figure 1: Structural schematic of the biogas plant (BEM-100): 1-reactor; 2-water seal; 3-compressor; 4-receiver; 5-collector; 6-spargers; 7-inlet chamber; 8-distribution chamber; 9-shut-off valve; 10-solenoid valve; 11-pipeline; 12-valve.

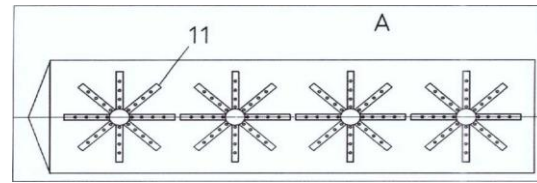


Figure 2: Arrangement of the mixing system inside the biochemical reactor: 11-perforated nozzles.

Figures 1-2 provide the structural overview and the in-reactor configuration of the sparger-based mixing system; the following section describes the timing control implementation and the relay settings used to realize the cyclic barbotage program.

4 CONTROL ALGORITHM AND OPERATING MODES

The biogas supply to the spargers can be controlled in two operating modes: manual and automatic. Such dual-mode implementation is practically important, since manual operation allows maintenance, commissioning, and emergency intervention, whereas automatic operation ensures stable and repeatable long-term mixing regimes.

4.1 Manual Mode

In the manual mode, the solenoid valve remains closed and does not participate in the mixing control. Mixing cycles are created by the operator through periodic opening and closing of a mechanical shut-off valve. This approach requires no additional control logic and may be acceptable for temporary operation and adjustment procedures. However, manual control is inherently sensitive to human factors. Deviations in switching time, inconsistent valve-opening duration, and irregular cycle spacing are typical and lead to low repeatability of the mixing pattern. From the process standpoint, such variability may affect hydrodynamic conditions in the digester, resulting in unstable circulation intensity between cycles and non-uniform disturbance of settled layers. Therefore, manual mode is mainly suitable for short-term operation or as a backup mode.

4.2 Automatic Mode

In the automatic mode, the mechanical shut-off valve is closed and cyclic mixing is achieved by the solenoid valve actuated by a time relay. In this implementation, the control strategy is based on a predefined switching schedule and corresponds to open-loop time-based control. The mixing algorithm can be formally represented as a cyclic sequence of discrete states: waiting → valve opening → gas supply (barbotage) → valve closing → waiting (Fig. 3).

Each cycle initiates gas injection through the spargers, forming a bubble flow that induces circulation of the liquid–sludge mixture and promotes periodic resuspension of settled solids.

The automatic approach provides several advantages relevant to practical digester operation:

- 1) High repeatability of the duty cycle and stable mixing intensity over time;
- 2) Reduced dependence on personnel, improving process stability and safety;
- 3) Consistency of operational documentation, enabling comparable results across operating periods;
- 4) Simplicity and robustness, since timing control can be implemented using standard industrial components.

For unambiguous specification and practical adjustment of the operating program, two timing parameters are introduced: T_{on} and T_{off} . The parameter T_{on} denotes the solenoid valve open duration, i.e., the time during which biogas is supplied to the spargers and active barbotage occurs. The parameter T_{off} denotes the pause duration between consecutive barbotage events, during which the valve remains closed. Accordingly, the duration of one complete operating cycle, T_{cycle} , is given by (1):

$$T_{cycle} = T_{on} + T_{off} \tag{1}$$

To characterize the intermittent operating regime more explicitly, the duty-cycle coefficient D can be introduced:

$$D = T_{on} / (T_{on} + T_{off}), \tag{2}$$

where D is the fraction of the cycle during which active gas injection occurs. This parameter can be used as a simple engineering indicator of mixing intensity and auxiliary energy demand. A lower value of D corresponds to shorter active gas supply periods and longer pauses, whereas a higher value of D indicates a more intensive barbotage regime. Thus, the intermittent pneumatic mixing process can be adjusted not only by changing the absolute values of T_{on} and T_{off} , but also by controlling the duty-cycle ratio.

For practical implementation, representative timing programs (T_{on} and T_{off} settings) used for intermittent pneumatic mixing are summarized in Table 1.

The proposed ranges are intended as practical engineering guidelines for commissioning and adjustment. The final settings should be selected based on reactor geometry, sparger configuration, substrate rheology, and the required level of hydrodynamic disturbance.

The values of T_{on} and T_{off} should be selected based on the process requirements and the digester configuration, considering factors such as reactor volume, sparger geometry, substrate properties, and the acceptable level of hydrodynamic disturbance. In practice, periodic rather than continuous gas mixing is often preferred because it reduces energy consumption and avoids excessive shear, while still preventing long-term sedimentation and stratification.

For reliable operation and reproducibility, the selected settings should be recorded in the operating documentation (relay configuration sheets, maintenance logs, or standard operating procedures). This enables consistent operation, simplifies maintenance, and improves transparency of the experimental and industrial results obtained from the reactor.

The wiring of the automation actuators (the time relay and the solenoid valve) is shown in Figure 4. A generalized connection diagram of the time relay and the solenoid valve is presented in Figure 5.

Table 1: Example timing programs for intermittent pneumatic mixing.

Program	T_{on} (gas injection)	T_{off} (pause)	Application note
A (commissioning)	10–30 s	10–30 min	commissioning / checking spargers
B (standard intermittent)	30–90 s	1–3 h	routine operation, low energy consumption
C (enhanced mixing)	60–180 s	30–90 min	increased solids tendency / stratification risk
D (literature-based)	60–120 s	4–6 h	recommended in [6] for similar configurations

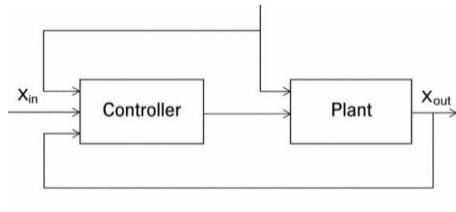


Figure 3: Automatic control scheme.

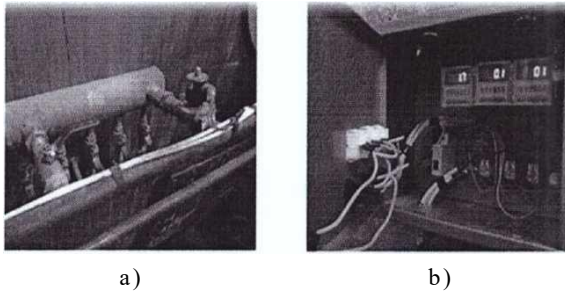


Figure 4: Connection of the solenoid valve and the time relay for substrate mixing in the biochemical reactor: a) general view of the installation; b) relay control panel with wiring.

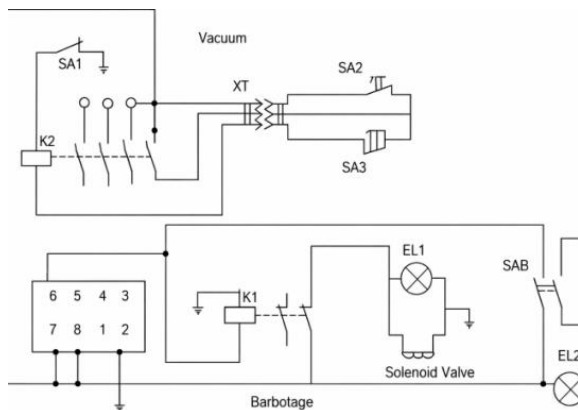


Figure 5: Generalized wiring diagram of the time relay and the solenoid valve.

The technical specifications of the DH-48S-S time relay used for implementing the timing control are summarized in Table 2.

Overall, the specifications in Table 2 confirm that the DH-48S-S relay is suitable for implementing cyclic time-based control of a 220 VAC solenoid valve in the proposed mixing system. In the following subsection, the practical implementation on the BEM-100 setup and the observed operational effects of timer-controlled barbotage are described.

Table 2: Technical specifications of the DH-48S-S time relay.

Specification	Value
Model	DH48S-S
Product type	Repeat cycle time relay
Time setting range	0.01–99.99 s / 0.1–999.9 s / 0.1–99h 59min
Operating mode	Repeat cycle (cyclic on/off)
Setting method	Dial switch
Power supply	220 VAC, 50/60 Hz
Power consumption	≤ 2 W
Contact form	SPDT (1NO + 1NC)
Relay contact rating	5 A @ 250 VAC
Display type	4-digit LED (8-segment)
Number of pins	8
Operating temperature	0...+50 °C
Relative humidity	≤ 95% RH (non-condensing)
Overall dimensions (W×H×D)	48 × 48 × 110 mm
Mechanical life	≥ 1 × 10 ⁶ operations
Weight	≤ 200 g

4.3 Practical Implementation and Observations

The proposed automation scheme was implemented using a DH-48S-S time relay and a standard 220 VAC solenoid valve installed in the biogas supply line. The configuration was tested on the BEM-100 biogas plant setup (see Fig. 1). Commissioning was performed by configuring the relay to generate periodic barbotage cycles defined by the timing parameters T_{on} (valve open duration) and T_{off} (pause duration).

The described automation scheme can be implemented using a DH-48S-S time relay and a standard 220 VAC solenoid valve installed in the biogas supply line, as illustrated by the BEM-100 biogas plant configuration (see Fig. 1). Commissioning is performed by configuring the relay to generate periodic barbotage cycles defined by the timing parameters T_{on} (valve open duration) and T_{off} (pause duration). The selection of appropriate timing values depends on reactor volume, sparger geometry, and substrate properties, and should follow the engineering guidelines summarized in Table 1. A structured comparison of the key operational characteristics of manual and automatic mixing modes is presented in Table 3.

Table 3: Comparative characteristics of manual and automatic pneumatic mixing modes.

Parameter	Manual mode	Automatic mode
Control principle	The operator opens and closes the shut-off valve manually	The solenoid valve is actuated by a time relay
Cycle repeatability	Depends on operator actions	Defined by T _{on} and T _{off} settings
Operation during unattended periods	Limited or absent	Possible according to a preset switching program
Main limitation	Human-factor variability	No feedback from pressure, gas flow rate, or temperature sensors
Practical effect	Irregular mixing frequency and duration	Stable cyclic barbotage and reduced operator dependency

ompared with manual switching, the automatic mode provided improved repeatability of the mixing duty cycle. Timer-based actuation reduced operator-dependent variability, including inconsistent valve opening time and irregular cycle spacing. Accordingly, cyclic barbotage could be performed according to a predefined schedule, which simplifies routine operation and reduces the need for continuous operator intervention.

The dual-mode (manual/automatic) implementation supports practical maintainability: the manual shut-off valve enables commissioning, adjustment, and emergency operation, whereas the solenoid valve controlled by the time relay provides consistent long-term cyclic actuation. Overall, the implemented configuration demonstrates the feasibility of intermittent pneumatic mixing automation using standard low-cost industrial components without a programmable controller and without the use of feedback sensors.

5 DISCUSSION AND LIMITATIONS

The use of barbotage as a mixing method is consistent with the general concept of gas-driven mixing in anaerobic reactors, where the objective is to maintain sufficient medium homogeneity while minimizing additional energy demand and mechanical complexity. In the proposed system, intermittent operation is implemented by means of a time relay and a solenoid valve, i.e., mixing intensity is indirectly regulated through cyclic gas supply. This approach corresponds to reported conclusions indicating that intermittent mixing regimes can be technically feasible and energetically advantageous in anaerobic digestion applications [4], [5].

It should be noted that the engineering assessment of automation benefits in this review is based on operational and structural arguments rather than

direct measurement data. The energy-related advantage of the intermittent mode is discussed in terms of reduced active gas-supply duration and lower duty-cycle operation. Published studies confirm that compressor operating time under intermittent schedules is substantially lower than under continuous agitation, with reported duty-cycle reductions of 60–90% depending on T_{on}/T_{off} combinations [8], [9]. Future work should address direct measurements of compressor energy consumption for varying duty-cycle configurations.

At the same time, the proposed solution is characterized by limitations inherent to time-based actuation. The control program is defined by fixed time intervals and does not employ feedback from process variables (e.g., gas-line pressure, gas flow rate, or reactor temperature). Therefore, variations in operating conditions may require adjustment of the timing parameters to maintain stable and repeatable performance. In addition, because the control scheme is implemented in an open-loop manner, deviations caused by external disturbances cannot be automatically compensated.

From an operational perspective, the reliability of the barbotage regime depends on the integrity of the pneumatic circuit, including gas-line tightness and proper functioning of the compressor and the valves. Furthermore, the long-term stability of mixing performance is influenced by the condition of the perforated nozzles, since clogging or fouling may reduce gas distribution uniformity and alter the effective mixing intensity. Consequently, regular inspection and maintenance of the gas distribution elements is recommended to ensure consistent operation of the pneumatic mixing system.

6 CONCLUSIONS

This paper reviews the engineering principles and practical implementation of automated barbotage

substrate mixing in biogas plants, utilizing biogas generated during anaerobic digestion as the working medium. A pneumatic mixing scheme is described, including biogas withdrawal from the reactor headspace, passage through a water seal, accumulation in a receiver, and supply to a collector with subsequent distribution to spargers equipped with perforated nozzles. The dual-mode (manual/automatic) control architecture is analyzed with respect to repeatability, operational simplicity, and suitability for small-scale installations.

The literature consistently supports that timer-controlled intermittent barbotage provides more repeatable operating conditions compared with manual switching, reduces operator-dependent variability, and lowers compressor duty cycle relative to continuous agitation [9], [5]. The duty-cycle coefficient D , defined as the ratio $T_{on} / (T_{on} + T_{off})$, is identified as a key engineering indicator linking mixing intensity to energy demand. Practical timing programs (T_{on} ranging from 10 s to 3 min; T_{off} from 10 min to 6 h) cover a wide range of operational scenarios from commissioning to routine operation.

The reviewed approach is practically significant for small-scale and farm biogas plants, where complex programmable automation may be economically unjustified. The use of standard industrial components - a time relay and a solenoid valve - makes the system relatively simple, maintainable, and suitable for implementation under field conditions. Future research directions include closed-loop control with process feedback, long-term evaluation of mixing schedules under varying substrate compositions, and integration with digital monitoring systems.

ACKNOWLEDGMENTS

We acknowledge support by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) and the Open Access Publishing Fund of Anhalt University of Applied Sciences.

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