

3D Printed Neutralization Modules for Gas Boiler Condensate: A Scalable Approach to pH Control

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Introduction

In the European Union (EU), natural gas accounted for 30.9 % of final energy consumption in households in 2022, making it the most used energy source in this sector. It was followed by electricity at 25.1 % and renewables and waste at 22.6 % [1]. This widespread use of natural gas for heating is reflected in the number of gas boilers installed across Europe. As of 2023, there are over 90 million gas and oil boilers in the EU, with a new boiler being installed every eight seconds [2]. Along with the increasing demands for increasing the efficiency of these devices, it is also necessary to take into account the consequences that these measures bring, such as condensation of flue gases in the heat exchanger area. Given that the sensible heat loss of flue gases is the dominant loss, increasing efficiency is always associated with an increase in condensate production [3]. By partial or complete transition from fossil natural gas or other hydrocarbons such as propane-butane to renewable hydrogen in the future, the problem will not disappear; on the contrary, it will be higher due to the higher amount of hydrogen in the fuel.

The U.S. Environmental Protection Agency (EPA) states that the optimal pH range for most aquatic organisms is between 6.5 and 9 [4]. Condensate from gas condensing boilers typically has a pH between 2.0 and 4.0, making it acidic and potentially harmful to drainage systems if not neutralized. A cost-effective method for neutralizing this acidic condensate is using inexpensive materials like dolomite [5].

This study was aimed on description of originally designed, scalable 3D printed neutralisation module filled with different materials in order to achieve the acceptable pH of the condensate at the outlet of the module.

Materials and Methods

The experimental testing rig was designed specifically for this study. It consisted of a collection vessel with a maximum capacity of 1 m³, which was used to store condensate. The condensate was sourced from a local heating facility in the city of Odry, equipped with two hot water boilers connected to a district heating system. From the collection vessel, the condensate flowed through a regulation valve and a flow meter before entering the neutralization module. Sampling points were installed at both the inlet and outlet of the module to measure the pH levels. Outlet water was stored in the second collection vessel.

Three neutralization module designs, each with identical external dimensions of 200 x 200 x 200 mm, were tested. These designs were optimized to maximize the reaction efficiency between the condensate and the neutralizing material while minimizing material usage. Additional design priorities included scalability and ease of connectivity between multiple modules.

The modules were filled with one of two neutralizing materials: dolomite or a by-product of lime hydration from a specific technological process. These materials were chosen to evaluate their effectiveness in neutralizing the acidic condensate under controlled conditions.

Table 1: Sieve analysis of neutralising materials

Fraction [mm]	Dolomite		By-product of the hydration of lime	
	Weight [g]	Share [%]	Weight [g]	Share [%]
> 8	6	0.2	8	0.3
> 4	1039	36.7	1050	37
> 2	1717	60.6	1690	59.8
> 0.5	40	1.4	45	1.6
< 0.5	31	1.1	30	1.1
Sum	2833	100	2823	100

Results and discussion

For the neutralization of condensate formed by condensation of flue gas produced by the combustion of natural gas, the by-product of the hydration of lime in a specific technology proved to be the best, achieving stability in a long-term test (40 hours), with a pH at the outlet between 9 and 10. Dolomite showed lower stability and also lower reaction ability with pH ranging between 5 and 6 (in the case of condensate pH at the inlet 3). The dolomite performance was in line with the study of Horák et al. [5]

The results emphasize the importance of synergistic design between the neutralization module and the selected material. The most effective module designs leveraged enhanced flow paths and increased surface contact, which amplified the lime by-product's natural reactivity. This finding underscores the necessity of tailoring module design to the specific properties of the neutralizing material to achieve optimal performance.

Conclusion

This study evaluated the performance of two neutralization materials—dolomite and a by-product of lime hydration—in conjunction with scalable 3D-printed neutralization modules for controlling the pH of acidic condensate from gas condensing boilers. The experiments demonstrated the critical importance of both material properties and module design in achieving effective and sustainable neutralization.

The by-product of lime hydration proved to be significantly more effective, maintaining a stable pH range of 9 to 10 over a 40-hour test period. This stability highlights its potential for long-term and high-intensity applications. In contrast, dolomite achieved only a moderate pH stabilization range of 5 to 6, suggesting its suitability for less demanding scenarios or as part of a hybrid approach to reduce costs.

The modular design of the neutralization units proved effective, allowing for adaptability and scalability in practical applications. Modules with optimized flow paths and enhanced surface contact consistently improved material performance. This synergy between material and module design underscores the potential for further optimization in future systems. Building upon the findings of this study, several avenues for future research are recommended. First, exploring pre-treatment methods, such as thermal or chemical activation, could significantly enhance the reactivity and long-term stability of dolomite, making it a more effective neutralization material. Additionally, testing hybrid materials that combine dolomite with lime by-products or other neutralizing agents offers the potential to balance cost-efficiency with performance. Finally, extended field trials in real-world boiler systems are essential to assess the durability and effectiveness of both the neutralization materials and the module designs under practical operating conditions. These efforts would further refine the technology and ensure its applicability in diverse scenarios.

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