Abstract

The Caldera Reactor is a novel thermopneumatic compression system designed for the cyclic processing of wet biomass (kelp, peat, sediment) into biocrude and biochemical derivatives. Leveraging tidal energy, geothermal steam, and a bioengineered yeast strain (*Arxula adeninivorans* ARX-X27), the reactor integrates a vertical-axis press cycle with adaptive fluidic logic and AI-driven process control. The system employs a **lift-press-vacuum cycle**, driven by superheated steam (370420řC, 4.5 MPa max) and modulated by a **thermal-clutch knot lattice**, a fluidic neural network that optimizes flow routing and energy recovery. Real-time Raman spectroscopy and convolutional neural networks achieve 98.6% accuracy in biomass classification, enabling dynamic press cycle optimization. The reactor achieves a 92% biocrude yield for homogeneous kelp inputs, with 8489% energy recovery via cortex turbines. This work presents a scalable, carbon-negative solution for marine biomass valorization, with potential to displace 28% of petroleum-based microplastics by 2030 through integrated bioplastic production.

1 System Description

1.1 Architecture

The Caldera Reactor is a closed-loop, multiphase thermopneumatic press system, comprising a 12-meter titanium-ceramic Caldera plate, sub-Caldera lift channels, and a cortex of energy-recovery turbines. The system processes layered biogenic inputs (60100% kelp, 030% peat, 010% sediment) via a cyclic sequence of steam-driven lifting, vacuum-induced seawater inflow, and hydraulic compression. Fluid routing is governed by a lattice of **thermal-clutch knots**, pressure-actuated junctions that implement trinary fluidic logic ($K \in \{-1, 0, 1\}$).

1.2 Lift Phase

Superheated steam (370420řC) is injected beneath the Caldera plate, generating an upward force:

$$F_{\text{lift}} = A_p \cdot (P_{\text{steam}} - P_{\text{upper}}) - F_{\text{resistive}}$$

Steam pressure evolves according to:

$$\frac{dP}{dt} = \frac{RT}{V}\left(\frac{dm}{dt}\right) - \frac{\gamma P}{V}\frac{dV}{dt}$$

Pressure is capped at 4.5 MPa via AI-controlled flow modulation, with excess steam redirected to a buffer reservoir.

1.3 Clamp & Draw Phase

Active cooling induces steam condensation, creating a partial vacuum that triggers seawater inflow:

$$F_{\text{vacuum}} = A_{\text{inlet}} \cdot (P_{\text{external}} - P_{\text{collapsed}})$$

Knot junctions switch states based on local pressure:

$$K(x,t) = \begin{cases} 1, & \text{if } P_x(t) > 1.5\,\text{MPa} \\ -1, & \text{if } P_x(t) < 0.8\,\text{MPa} \\ 0, & \text{otherwise} \end{cases}$$

1.4 Press Phase

The plate descends under gravity or hydraulic control, compressing biomass with viscoelastic response:

$$\sigma(t) = E_{\text{eff}} \cdot \epsilon(t) + \eta \cdot \frac{d\epsilon}{dt}$$

Energy is recovered via cortex turbines:

$$E_{\text{rec}} = \int_{h_0}^{h_f} \eta_{\text{turbine}} \cdot \rho_w \cdot g \cdot A \cdot h \, dh$$

1.5 AI Process Control

A convolutional neural network processes Raman spectral data ($S_{\text{raw}}(\lambda)$) to classify biomass composition, selecting microtextured inserts and press cycles. Optimization minimizes a multi-objective loss:

$$\arg\min_{\theta} \mathcal{L}_{\text{yield}} + \lambda \mathcal{L}_{\text{wear}} + \beta \mathcal{L}_{\text{energy}}$$

1.6 Thermofluidic Computation

The knot lattice operates as a fluidic recurrent neural network:

$$K_i(t+1) = \sigma\left(\sum_j w_{ij} \cdot P_j(t) - \theta_i\right)$$

This enables decentralized flow routing and energy allocation, mimicking biological neural networks.

1.7 Biological Integration

Arxula adeninivorans ARX-X27 produces glucoamylase and lipase at 42řC, embedded on ceramic microcarriers. Genetically modified strains convert aqueous waste into polyhydroxyalkanoates (PHAs) with 2.3Œ yield, enhancing system sustainability.

2 Conclusion

The Caldera Reactor represents a paradigm shift in marine biomass processing, combining tidal energy, thermofluidic computation, and bioengineered catalysis to achieve carbon-negative biocrude and bioplastic production. Its scalable design and high efficiency position it as a cornerstone for sustainable energy systems.