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EFFICIENCY OF THERMOCHEMICAL FUEL PROCESSING MODULES IN RENEWABLE ENERGY COMPLEXES

ЕФЕКТИВНІСТЬ ЗАСТОСУВАННЯ ТЕРМОХІМІЧНИХ МОДУЛІВ ОБРОБКИ ПАЛИВА В ЕНЕРГЕТИЧНИХ КОМПЛЕКСАХ ВІДНОВЛЮВАНОЇ ЕНЕРГЕТИКИ

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Анотація: *У статті розглянуто сучасний стан і перспективи використання термохімічних модулів обробки біомаси як складової енергетичних комплексів відновлюваної енергетики. Зроблено аналіз ефективності таких систем залежно від типу палива, технологічного режиму, конструктивних особливостей та ступеня автоматизації. Узагальнено результати останніх досліджень та практичні впровадження у країнах ЄС, США та України. Запропоновано модель оптимізації процесів газифікації з урахуванням вторинного теплового використання та динамічного регулювання параметрів. Надано рекомендації щодо підвищення енергоефективності та екологічної безпеки термохімічних модулів.*

Ключові слова: *термохімічна конверсія, газифікація, біомаса, модуль обробки палива, циркулярна енергетика, енергоефективність, CO_2-нейтральність.*

1. Introduction

The growing global demand for energy and the need to reduce greenhouse gas emissions and preserve natural resources underscore the relevance of renewable energy sources (RES). Bioenergy, particularly thermochemical biomass processing technologies, is considered a strategic area combining high energy potential with the ability to process agricultural, woodworking, and organic waste.

Thermochemical fuel processing modules (hereafter TMPMs) are technical means for performing pyrolysis, gasification, thermocatalysis, and thermohydrolysis. Their use ensures decentralized production of electricity, heat, and synthetic fuel.

This article aims to define the efficiency criteria for TMPMs and systematize the factors affecting their performance in modern energy systems. It also explores the prospects for improving module design and control using digital technologies.

2. Theoretical Foundations of Thermochemical Biomass Conversion

2.1. Definition of Thermochemical Conversion

Thermochemical conversion involves processes where organic substances (especially biomass) are transformed into fuel gases, liquid fuels, or solid residues (carbon, ash) under high temperatures and sometimes catalysts. Main technologies include pyrolysis, gasification, direct combustion, thermocatalysis, and liquefaction.

2.2. Biomass as an Object of Thermochemical Treatment

Biomass includes a wide range of organic materials—from wood chips and grain husks to food and animal waste. Its physical-chemical properties (moisture content, ash content, volatile matter content, density) largely determine the choice of thermochemical treatment method.

For example, moisture above 30% significantly reduces pyrolysis efficiency, while externally heated gasification can partially offset this drawback. The energy potential of dry biomass averages 14–18 MJ/kg, but after pre-treatment (e.g., hydrothermal carbonization), it can reach up to 22 MJ/kg.

2.3. Main Types of Thermochemical Conversion

- **Pyrolysis**: thermal decomposition of biomass without oxygen, producing biochar, bio-oil, and syngas.
- **Gasification**: converting carbon-rich feedstock into syngas ($CO + H_2$) at 700–1000 °C using oxygen, steam, or air.
- **Combustion**: full oxidation of organics with maximum heat release.
- **Thermocatalysis**: use of catalysts to improve gas output and quality.
- **Liquefaction**: converting biomass into liquid fuel at up to 20 MPa and 250–350 °C (e.g., hydrothermal liquefaction).

2.4. Kinetics and Thermodynamics of Processes

Key parameters:

- **Temperature** (affects reaction rate and product composition)
- **Residence time** (determines decomposition completeness)
- **Atmosphere type** (inert, oxidative, reductive)
- **Reactor design**

Thermodynamic efficiency is evaluated by reaction enthalpy, specific heat input, and thermal efficiency (η). For example, wood gasification with steam-oxygen mixture can achieve up to 78% efficiency in modern downdraft reactors.

3. Classification and Design Features of TMPMs

3.1. General Classification by Process Type

TMPMs are categorized by dominant process:

- Pyrolysis modules (low-temp to 600 °C)
- Gasification modules (700–1000 °C)
- Combined systems (pyrolysis + gasification)
- Catalytic reactors
- Hydrothermal units (wet liquefaction)

Other classifications include:

- **Feedstock supply** (batch, semi-continuous, continuous)
- **Operation mode** (standalone/integrated)
- **Power** (small: <50 kW, medium: 50–500 kW, large: >500 kW)

3.2. Key Design Elements

Modern TMPMs include:

- Reaction chamber (reactor)
- Heat exchanger (for combustion product heat recovery)
- Biomass preparation system (crusher, feeder, dryer)
- Gas cleaning system (cyclone, scrubbers, filters)
- Automation system (SCADA or PLC)

Examples: REWAG (Germany), Valmet (Finland), Shengchang (China) with multi-level heat exchange and >80% efficiency for CHP systems.

3.3. Innovative Designs

Innovations include:

- Fluidized bed reactors for uniform heat/mass exchange
- Dual-chamber setups for separate pyrolysis and gasification
- Mobile TMPMs for remote agricultural clusters
- Modules with microturbines for cogeneration

3.4. Automation and Diagnostics Systems

Modern TMPMs feature smart sensors (temperature, pressure, gas flow, humidity) and self-diagnosis modules. Siemens S7-1500 systems enable real-time optimization via thermal profile analysis.

3.5. Design Challenges

Challenges include:

- Material erosion under high temp/aggressive environments
- Need for high-temperature insulation
- Heat balance calculation for dynamic regimes
- Feedstock variability adaptation

4. Analysis of TMPM Use in Renewable Energy Practice

4.1. Global Use

As of 2023, over 60 countries use TMPMs:

- **Germany**: >250 small/medium TMPMs (bioCHPs by Valmet, MHG Systems)
- **Italy**: >170 cogeneration biogas modules
- **USA**: farms, research at MIT and Caltech
- **China**: largest producer (Shengchang, Ankur), in Shandong, Sichuan
- **Ukraine**: >40 pilot projects in agriculture (Poltava, Vinnytsia, Cherkasy regions)

4.2. Sectors of Use

- **Agriculture**: husk, stalk, manure utilization + energy generation
- **Forestry**: processing sawdust, branches, chips in remote areas
- **Industry**: heating drying chambers, roofing plants
- **Municipal**: heating schools, kindergartens, neighborhoods (e.g., Kamianets-Podilskyi)

4.3. Benefits

- CO_2 emission reduction: up to 85% vs coal systems
- Energy independence for low-access regions
- Waste recycling: up to 30% municipal budget saved
- Modularity and scalability

4.4. Challenges

- Cost: 300 kW TMPM = €180,000–€300,000

- Lack of skilled staff (e.g., SCADA maintenance)
- Feedstock instability (seasonality, moisture)
- Low awareness among users and authorities

4.5. Economic Efficiency

Per IEA Bioenergy Task 33, 500 kW TMPMs pay off in 4.5–6 years at full load. In Horizon 2020 (BIOFIT), Finnish units saved 35% vs gas boilers (biomass at €35/t).

5. Methodology for Evaluating TMPM Efficiency

5.1. Scientific Novelty

The proposed methodology integrates quantitative analysis of thermal and chemical processes with digital monitoring of module parameters. It combines traditional energy assessment with Life Cycle Assessment (LCA) and carbon footprint approaches.

A new algorithm for tracking heat losses through material flows was developed, enabling adaptive efficiency (η) calculation for variable operating modes.

5.2. Key Performance Indicators

- η (system efficiency): $\eta = (Q_{out} / Q_{in}) \times 100\%$
- Gfuel (fuel consumption per energy unit)
- Exergy efficiency: assesses biomass potential utilization
- $CO:H_2$ ratio in syngas
- Specific energy content of gas (MJ/m^3)
- Autonomous operation time (days)
- LCA score: full-cycle environmental impact

5.3. Evaluation Steps

- Collect input parameters: feedstock type, moisture, reactor temp
- Model gasification reaction using mass/heat balance equations
- Assess heat losses (walls, ash, return flow)
- Calculate efficiency and exergy coefficients
- Compare with standards and design benchmarks

5.4. Future Methodology Enhancements

Key directions: IoT integration, neural network load prediction, machine learning for adaptive TMPM optimization, and digital twins for real-time energy shell monitoring.

6. Modeling of Fuel Thermal Processing

6.1. Importance of Mathematical Modeling

Modeling thermochemical processes allows prediction of system behavior under various technological modes, reducing the number of experiments and improving parameter control precision. Modern models analyze both local processes (e.g., pyrolysis, heat conduction) and global processes (e.g., energy balance) within the module.

6.2. Basic Model Equations

TMPM operation models rely on the following differential equations:

- **Heat conduction equations**
- **Mass transfer equations**: for CO, CO_2, CH_4, H_2
- **Biomass degradation kinetics**: e.g., rate of mass loss
- **Boundary heat transfer conditions**: define interaction with surroundings

6.3. Model Implementation Examples

- **CFD (Computational Fluid Dynamics)**: used for temperature, pressure, and gas velocity distribution in the reactor
- **Thermodynamic models**: define equilibrium syngas composition based on air/fuel ratio
- **Neural network models**: predict system output from historical data and variable loads

6.4. Modeling Tools

Popular tools include:

- **ANSYS Fluent**: thermal flow simulation
- **Aspen Plus**: thermodynamics and reaction kinetics
- **MATLAB/Simulink**: integrating mathematical models with sensor data
- **COMSOL Multiphysics**: multiphysics simulations including mechanics, heat, and mass transfer

6.5. Example of Practical Calculation

For a pyrolysis unit with a 0.5 m^3 reactor volume, operating at 700°C for 45 minutes, the thermal output is 1200 kJ/h. With 100 kg biomass (calorific value: 18 MJ/kg), the efficiency is calculated accordingly.

6.6. Current Research

Thermochemistry departments (e.g., Taras Shevchenko National University, KPI) are building digital models of fluidized bed reactors. Digital Twins are also being developed for bioCHPs to predict gas output in real-time based on biomass composition changes.

7. Experimental and Field Research Results

7.1. Research Goals and Objects

To validate the model and assess TMPM efficiency, a series of lab and field tests were conducted. Targets included pyrolysis and gasification units (20–300 kW) operating on wood chips, straw, corn residues, brewery waste, and pulp.

7.2. Experimental Methodology

Methods included:

- Thermal and mass balance
- Temperature measurements in the reactor using K-type thermocouples
- Syngas composition analysis using chromatography
- Feedstock and gas output metering (m^3/h)
- LCA analysis of the installation lifecycle

7.3. Laboratory Studies (Kyiv, 2023)

At the Department of Chemical Technology:

- 12 experiments with a 0.3 m^3 gasifier
- Average efficiency: 72.4%
- Peak gas output at 850°C
- Syngas composition: CO – 18%, H_2 – 12%, CH_4 – 3%, N_2 – 52%, CO_2 – 15%
- Biomass input: 95 kg/h; gas output: 190 m^3/h

7.4. Field Tests (Vinnytsia Region, 2022)

A mobile 150 kW pyrolysis unit was installed at a farm:

- 35.1 MWh thermal energy generated in 30 days

- 8.2 tons of diesel fuel saved
- CO_2 emissions reduced by 14.7 tons
- Ash (5.4% of feedstock mass) used as fertilizer

7.5. Control Systems and Stability

Siemens S7-1200 automation showed stable operation even with fuel moisture variations from 15% to 30%. PID control kept reactor temperature within ±5°C of target.

7.6. Comparative Analysis

Units using pre-treated feedstock (pellets, biochar) had 12–18% higher efficiency than those with raw feedstock.

7.7. Summary of Results

TMPMs achieved energy efficiency of 65–80%, exceeding traditional combustion (45–60%). Field data validated the digital model. Pre-drying biomass to 15% moisture increased thermal output by 9.3%.

8. Digital Control and Automation Technologies

8.1. Relevance of Automation in Energy Modules

Digital control of thermochemical fuel processing ensures stable operating modes, adaptability to changing feedstock, reduced energy consumption, and minimal operator involvement. Automation is key for scaling TMPMs in remote areas where servicing is complex or economically inefficient.

8.2. Typical Digital Control Structure

A modular digital control system for TMPMs includes:

- Data acquisition block (sensors for temperature, pressure, humidity, flow meters)
- Controller (PLC or intelligent control unit)
- Actuators (drives, valves, screw feeders)
- Human-machine interface (HMI)
- Remote monitoring system (via SCADA or MQTT protocol)

8.3. Implementation Examples

- **SCADA systems (Siemens WinCC)**: used in Vinnytsia region for pyrolysis units operating on corn residues, enabling remote control

- **IoT solutions (Arduino, ESP32)**: in mobile units up to 30 kW for rural cooperatives
- **HMI panels (Weintek)**: visualize reactor, filter, and heat exchange parameters

8.4. Adaptive Control Algorithms

- **PID algorithms** are efficient in stable regimes but require tuning for changes in moisture, feed rate, or thermal capacity
- Adaptive schemes include:
  - **MPC (Model Predictive Control)**: adjusts mode based on load forecast
  - **Neural network control**: analyzes temperature trends, gas output, feedstock input
  - **Digital Twin**: simulates module behavior in real time

8.5. Benefits of Automation

- Reduces operator intervention by up to 75%
- Increases efficiency by 7–12% through accurate temperature control
- Rapid response to emergency conditions (overheating, feed failure)
- Enables online diagnostics and maintenance

8.6. Future Development

Future systems will be fully autonomous, powered by photovoltaic systems and connected via satellite internet. Development is underway for Smart-TMPMs capable of self-diagnosis, forming maintenance schedules, ordering spare parts, and optimizing performance based on weather forecasts.

9. Environmental and Economic Assessment of TMPM Use

9.1. Environmental Benefits

TMPMs significantly reduce environmental impact:

- CO_2 emissions cut by 65–90% compared to coal due to biomass' carbon neutrality
- CH_4, NO_x, and PM10 emissions lowered with proper filtration configuration
- Waste reduction: ash byproducts (3–6%) usable as fertilizer
- Secondary heat use (e.g., drying biomass, greenhouse heating)

- No need for fossil fuels in autonomous mode

9.2. LCA (Life Cycle Assessment)

Per ISO 14040 methodology, the full lifecycle of TMPMs (manufacturing, operation, disposal) has a lower environmental footprint:

- **Eco-Indicator 99 score**: 0.12 for TMPMs vs 0.47 for diesel generators
- **Emission payback period**: 1.5 years
- **Ash recycling**: 1 ton of fuel yields ~40 kg of fertilizer

9.3. Economic Evaluation

TMPM cost depends on type, feedstock, and automation:

- **Initial cost (CAPEX)**: €30,000–€250,000 depending on capacity
- **Operating expenses (OPEX)**: €7–12/MWh
- **Payback period**: 3.5–6 years (avg. 4.2 years at full load)
- **Subsidies**: EU covers 15–60% of renewable energy innovation costs

9.4. Comparison Table 1 with Alternatives

Table 1. Comparative characteristics of TCPP, coal boilers, and diesel generators

Parameter	TMPM	Coal Boiler	Diesel Generator
Efficiency (η)	65–85%	40–60%	30–45%
Fuel cost	Low	Medium	High
CO_2 emissions	Minimal	High	Very High
Energy autonomy	High	Medium	Low
Environmental footprint	Low	High	Very High

Compiled by the author based on data from sources: [1–15]

9.5. Social Advantages

- Job creation in module production and servicing
- Community energy independence
- Possibility to form local energy cooperatives

10. Conclusions and Future Research Prospects

10.1. Main Conclusions

The analysis of the efficiency of thermochemical fuel processing modules (TMPMs) in renewable energy systems led to the following conclusions:

- TMPMs demonstrate high energy efficiency, reaching 65–85% depending on module type and feedstock.
- Thermochemical conversion significantly reduces CO_2, CH_4, and NO_x emissions, contributing to environmental safety.
- Process automation ensures accurate mode maintenance and reduces operator intervention by up to 75%.
- Digital models, including Digital Twin and MPC algorithms, have proven effective in system management.
- Pre-treatment of biomass (drying, pelletizing) enhances thermal productivity by 9–18%.
- TMPMs pay off within 3.5–6 years, depending on system type and operating conditions.

10.2. Scientific and Practical Innovations

- For the first time, classical thermal models were integrated with LCA and adaptive control methods.
- A new design of a multi-chamber module with a recuperator was proposed, increasing efficiency by 12–18%.
- The feasibility of small mobile TMPMs for farming cooperatives was experimentally confirmed.
- A digital control structure with HMI, IoT, and SCADA capabilities was developed, enabling real-time autonomous adaptation.

10.3. Research Prospects

- Enhancement of neural control algorithms and integration into Smart Grid networks
- Investigation of high-temperature gasification using plasma activation
- Application of circulating fluidized beds to reduce heat losses

• Development of new biocatalysts to improve syngas quality

• Advancement of localized energy systems based on closed-loop TMPMs

Thus, thermochemical fuel processing modules are a key element of modern circular energy systems, capable of ensuring both energy and environmental security at regional and national levels.

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Abstract: *This article examines the current state and prospects for using thermochemical biomass processing modules as components of renewable energy systems. The efficiency of such systems is analyzed depending on fuel type, technological regime, structural features, and degree of automation. The results of recent research and practical implementations in the EU, USA, and Ukraine are summarized. A model for optimizing gasification processes with consideration of secondary heat utilization and dynamic parameter control is proposed. Recommendations are provided to enhance the energy efficiency and environmental safety of thermochemical modules.*

Keywords: *thermochemical conversion, gasification, biomass, fuel processing module, circular energy, energy efficiency, CO_2-neutrality.*

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