NOVEL APPROACHES TO COMBUSTION OF ORGANIC FUELS

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1. THE ROLE OF COAL IN POWER ENGINEERING
2. TECHNOLOGIES AND PROBLEMS OF USING COAL IN POWER ENGINEERING
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4. COAL COMBUSTION
5. COAL CONVERSION TECHNOLOGIES
6. OTHER TYPES OF SOLID FUELS
7. NONCONVENTIONAL ENERGY TECHNOLOGIES

CONCLUSIONS
1. THE ROLE OF COAL IN POWER ENGINEERING
CLASSIFICATION OF SOLID FUELS

SOLID FUELS

ORGANIC FOSSIL FUELS
- Humus rocks (from plants and plankton)
  - Peat
  - Black coal
  - Brown coal
  - Synthetic solid fuels: coke; semi-coke
- Sapropelic rocks (from lake silt plankton)
  - Sapropelic coals (small ash content)
  - Sapropel
  - Combustible shales (high ash content)

BIOMASS
- Wood
  - Vegetative mass

MAN- CAUSED WASTES
- Municipal wastes
- Industrial wastes
- Agricultural wastes
## GEOLOGICAL RESOURCES

<table>
<thead>
<tr>
<th>Fuel</th>
<th>World reserves, billions, t.e.f.</th>
<th>Deposits in Russia, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas hydrates</td>
<td>23 000</td>
<td></td>
</tr>
</tbody>
</table>
| Uranium (thermal neutrons) (fast neutrons) | 300  
15 000                         |                       |
| Coal                                | 10 000                           | 50 %                  |
| Oil                                 | 840                              | 5 %                   |
| Natural gas                         | 350 - 600                        | 40 %                  |
| Liquid fuel (shales, bituminous rocks) | 490                             |                       |
| Peat                                | 5                                |                       |

Average annual consumption of fuels: 15 billions, t.e.f.  
Life capability: 3 000 years
GROWTH OF GENERATING POWER UNITS IN THE WORLD DEPENDING ON FUEL TYPE, GW

- Coal
- Hydro
- Gas
- Nuclear
- Oil
- Other fuels

Structure of electricity world production in 2003:
- Coal: 41% in 2010 (25% - Russia)
- 44% in 2030
NEW ENERGY STRATEGY FOR RUSSIA (2007)

Reduction of consumption share of heavy oil and gas in power industry on the basis of:
- Coal technologies
- Hydro power engineering
- Nuclear power engineering

Increasing the efficiency of gas-operating plants

Renewable energy sources

ENERGY SAVING
Potential in Russia – 40 % of total energy consumption
* SIBERIA – the coldest region in the world
  - 60% of fuel - for heating
  - 62% of heat in West Siberia is generated by 28 thousand boiler-houses

* SIBERIA – the most reach region in Russia in terms of energy resources
  - gas (85%), oil (65%), wood (50%), hydro energy (45%), geothermal energy;
  - coal makes up 80% of total reserves of RF or 23% of world reserves

Structure of fuel consumption at heat power plants

Russia
- Coal 25%
- Gas 69%

Siberian Federal District
- Coal 86%
- Gas 14%
2. TECHNOLOGIES AND PROBLEMS OF USING COAL IN POWER ENGINEERING
COAL CONVERSION METHODS

COMBUSTION
- Pulverized coal
- Fire-chamber with dry-slag removal
- Fire-chamber with slag-tap removal
- Fuel-bed
- Circulating fluidized bed
- Vortex

COAL IMPROVEMENT
- Water-coal fuel (slurry)
- Catalytic combustion
- Combustion in slag melt
- Direct coal oxidation in fuel cell (FC)

DEEPER CONVERSION OF COAL
- Pyrolysis
- Gasification
- Underground gasification
- Direct liquefaction (hydrogenation)
- Solution in supercritical water
- Combined technologies
2 STRATEGY: 1. Efficiency increase of heat power plants
2. CO2 sequestration (3 technologies)

H. Spliethoff

Loss in efficiency 10-15%!
15 MW industrial waste plant in Singapore (project).

G. Benelli et al.
1. Clean Coal Technology Demonstration Program (CCT) – USA, 1986
2. Combustion 2000 (C-2000) – USA
3. Thermie – EU
4. Joule II – EU
5. Environmentally clean power engineering – Russia, 1989:
   Environmentally clean heat plant on solid fuel
   (9 projects for 4 coal grades)
3. COMBUSTION PROCESSES
STRATEGY: Avoiding high level of NOx emission implies operation away from stoichiometric conditions, particularly applying ultra lean combustion (close to blowout limit). Practical implementation requires a trade-off between emissions and combustion stability and efficiency.
Flameless combustion (1991)
Flameless oxidation: FLOX®
MILD combustion
HiTAC = High Temperature Air Combustion

**Concept:** High-speed injection of fuel and hot oxidizer at intense re-circulation of combustion products.

**Advantages:** enlargement of reaction zone, reduction of temperature and $O_2$ concentration, drastic decrease in thermal NOx, etc.

**Purpose:** combustion of gas, coal, biomass, municipal wastes; gasification.

Combustion of propane and hot furnace gas mixture with admixture of $O_2$ (Blasiak, 2008): (a) – 21%, (b) – 10%
Drastic increase in the area of stable combustion due to swirling
**STRUCTURE OF SWIRL FLAMES**

Swirl number \( S = 1.0 \)

Reynolds number \( \text{Re} = 6800 \)

Equivalent ratio \( \Phi = 1.4 \)

Mixture velocity \( U_0 = 7.3 \text{ m/s} \)

Noise level \( 1.2 \text{ Pa (92 dB)} \)

Flame visualization

(a) - photography

(b) – UV sensitive ICCD Camera

(CH* radicals)

Instantaneous fields of velocity and vorticity (Particle Image Velocimetry)

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State contract by the Federal Goal-Oriented program: DEVELOPMENT OF TECHNICAL SOLUTIONS FOR DESIGN OF PULVERIZED-COAL BURNER, PROVIDING TWO-FOLD REDUCTION OF NOX

Large-scale fire test bench for investigation of pulverized coal combustion (power of 5 MW, fuel consumption of up to 1t/h)

Suggested approaches:
- Intra-burner thermal preparation of fuel with application of mechanically activated coal;
- Flameless combustion;
- Staged combustion

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\( \sigma \text{Flow} \) allows for simulation of 2-D and 3-D flows:
- inviscid
- viscous
- laminar
- turbulent (with different models of turbulence)
- gas-liquid
- with solid particles
- with combustion
- with account for phase transitions

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Coal particle trajectories, temperature and velocity fields in boiler P67 of Berezovskaya State district power plant -2
4. COAL COMBUSTION
One obvious method for a higher thermal efficiency in a traditional steam-turbine cycle is a use of higher pressure and temperature of steam, i.e. transition to supercritical steam. In the framework of “TERMI” international program, European countries plan to build till 2015 the coal-fueled plants with the power of 400-1000 MW and steam temperature of 600-700 °C, pressure of 30 MPa, and efficiency of up to 55 %. In Russia, similar research work is carried out based on the operation experience of a plant with performance of 720 tons of vapor per hour, pressure of 30 MPa and temperature of 650 °C at the Kashira State Regional Power Plant (operates since 1963), and at the boiler plant of the Russian Thermal Engineering Institute (operates since 1949).

Project of Russian Thermal Engineering Institute and “Em-Alyans”: 660 MW; 29.4 MPa; 610°C; 45%.

Problems: construction materials.
ENERGY SYSTEMS WITH HIGH TEMPERATURE STEAM TURBINES

**Principle:** additional superheating of steam up to 800 ÷ 1500°C before turbine for the purpose of increasing plant efficiency up to 55%.

**Superheating:** hydrogen combustion in steam

**Source of hydrogen:** coal (gasification)

**Project of the Federal Objective Program of RF** ("TURBOKON"; Inst. Thermophysics, …)
Advantages of ultrafine milling (5 - 40 mkm):
- Effect of mechanical activation
- Reduction of temperature of ignition
- Large increase in solid surface area
- High intensity of combustion
- Reduction of NOx

Possible applications:
- Using fine coal as main fuel in small gas-heavy oil boilers
- Using fine coal instead of gas and heavy oil for ignition and lighting in large coal-fired boilers
- Direct combustion of fine coal in gas-turbine units

Problems:
- Large energy expenses for ultrafine milling
- Blowing up of coal dust

Parameters:
- Mean coal size: 35 mkm
- Capacity: 150 kg/h
- Energy expenses: 25 kW h/t

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Combustion of ultrafine coal

Ultrafine milling without mechanical activation: 
\[ E = 190 \text{ kJ/mol} \]

Ultrafine milling with mechanical activation: 
\[ E = 70 \text{ kJ/mol} \]

2011: testing micro-coal burning at Berdsk Heat Station of 30 MW power

Diagram for ultrafine pulverized coal combustion
EFFICIENCY OF HEAT POWER PLANTS

Combined Cycle Plant (CCP) on natural gas

CCP with direct combustion of coal in gas turbine

CCP with coal gasification in flow under high pressure

CCP with coal gasification in fluidized bed under high pressure

Coal-fired HPP with REA and DENOX

Efficiency, %

Temperature before turbine

800 900 1000 1100 1200 °C
Production technology of **WCF** (65% of coal) based on ball mill and **cavitation** generator with plasticizer addition has been developed. Size of coal particles is about **50-70 mkm**.

**WATER-COAL FUEL (WCF)**

Pneumatic injector based on Coanda effect

Possibility for combustion of coal slimes with ash content of up to **50%**

**PLANS:**
1. Utilization of coal output wastes
2. Development of centralized systems of **WCF** preparation with further supply to boilers (up to 100 km)

**WCF** combustion in industrial boiler KE10-13 6 MW “Building block plant” (gas concrete) in Novosibirsk

*Building Block Plant, “Thermoprom”, Institute of Thermophysics*
EXPERIENCE ACHIEVED BY THE AUTHORS OF THE PROJECT ON WCF

1. Three pilot boiler setups with the power of 1.5, 3, 7 MW were constructed at "The building block plant" in Matveevka. Running time of up to 3 years. Burned fuels: black coal, anthracite, slurry.

2. Boiler RN-38 of 0.7 Gcal/h (Kemerovo) was converted from fuel-bed burning to combined burning with WCF. WCF–wastes of Berezovskiy concentration plant!

3. Boiler KVTS-20/150 of 25 MW (Berezovskiy, Kemerovo) was converted to combined burning of coal and WCF (from wastes of coal concentration).

4. Boiler KE 10/14 in Moshkovo was converted at the end of 2010 to WCF combustion with productivity of up to 4.8 Gcal/h and efficiency of up to 92%. Can operate on anthracite.

Boiler KE 10-13 produced at “The building block plant» (gas concrete) in Matveevka, Novosibirsk
Mazut-free plasma ignition of pulverized coal combustor

Advantages:
- Replacement of gas and mazut
- Decreasing mechanical underburning
- Stabilization of pulverized coal flame
- Reduction of toxic gases emissions

Plasma ignition system in city of Loyan (China)
5. COAL CONVERSION TECHNOLOGIES
Gasification – production of fuel gas (syngas) at incomplete oxidation of coal.

**Purpose:** production of thermal and electric energy; generation of hydrogen and synthetic liquid fuel (SLF).

**In the USSR in 1958:** 2,500 gas generators with capacity of 15 mln. tons of coal per year.

**Priority:** combine cycle coal gasification for energy production (binary cycle – gas fuel is combusted in gas turbine, products are fed into the boiler). First heat power plant of 100 MW – USA (1983).

**Gasifier types:** Winkler (with fluidized bed, 1926), Lurgi (with high pressure in the bed, 1932), Koppers-Totzek (with pulverized coal flow, 1945), Texaco (on water coal slurry, 1970), The Siemens Fuel Gasifier SFG™ (entrained-flow).

**Oxidizer:** oxygen, air, water.

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**World consumption of gas generated in gas generators (2001).**

<table>
<thead>
<tr>
<th>Sources</th>
<th>Consumption, GW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical production</td>
<td>18</td>
</tr>
<tr>
<td>Power production (combined cycle gasification)</td>
<td>12</td>
</tr>
<tr>
<td>Production of synthetic liquid fuel</td>
<td>10</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>40</strong></td>
</tr>
</tbody>
</table>

**Russian program «Environmentally clean power engineering»**

Project of Berezovsky plant of **8 GW in capacity (!):** 8 integrated coal gasification combined cycle plants.
THERMOCOKE CONCEPTION®

CJSC «Sibthermo», Krasnoyarsk

Steam, hot water
Carbon residue
Coke products, carbon sorbents
Steam, hot water

Products:

Air
Gas fuel
Gas combustion
Heat

Coal

Carbon residue

Air
Coal gasification in bed with air blowing and reverse thermal wave

Coal gasifiers

Gasifiers

Warm water

Fuel gas

Air

Coke

Blower

Return water from heating system

Blast

Hot water to the heating system

Smoke exhauster

CJSC «Sibthermo», Krasnoyarsk
“CARBONICA” TECHNOLOGY – the process of layer gasification of volatile coal components at air blowing under the mode of “reverse heat wave”. Gas composition: CO = 26%, H₂=22%...
Partial coal gasification in fluidized bed with air blow

Use of brown coal coke

1. Basic component of pulverized coal fuel for blowing into the blast furnace
2. Technology fuel for cement (alumina) plants
3. Patch fuel for metallurgy—substitute for classic coke
4. Feedstock for smoke-free briquettes

CJSC «Sibthermo», Krasnoyarsk
Gasifier with the liquid metal electrodes with capacity of 0.5 MW

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Plasma-vapor gasification of coal

Reactor, 100 kW (Gousinoozersk)

Synthesis gas: CO = 48%, H$_2$=49%, N$_2$=3%; $Q_{cd}=5000$ kcal/kg

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ENERGY COMPLEX FOR COAL CONVERSION

Institute of Combustible Fossils

Pressurized fluidized bed gasifier → Syngas → Molten carbonate fuel cell
- CO2
- Sulfur
- Heat

Fluidized bed boiler
- Coke
- Building material

Steem turbine

Chemical plant
- Hydrogen
- Methanol
- Ammonia
- Gas fuel
- Gasoline
- Chemicals

Gas Turbine
6. OTHER TYPES OF SOLID FUELS
Energotechnological application of solid fuels: *Shale pyrolysis.*

The world reserves of shale include 550 – 630 billion tons of crude shale oil – it is 3-4 times higher than explored reserves of oil.

Setups for shale pyrolysis have been constructed in the USSR (Narva) in 80-s and in Brasilia.

The scheme of thermal processing of shale in UTT-3000 setup with solid heat carrier (ash) – 3000 t/day:

Wood reserves in Russia – 26% of world reserves. Main reserves are concentrated in Siberia (11% of world reserves) and Far East.


The scheme of setup for production of power gas, heat energy and hot water
N = 100 kW

Tumen SC SB RAS
### SOLID MUNICIPAL WASTES (SMW)

The world problem: utilization of solid municipal wastes (SMW)

<table>
<thead>
<tr>
<th>Countries</th>
<th>SMW production, mln.t/year</th>
<th>Burning mln.t/year</th>
<th>%</th>
<th>Number of combustion plants</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>248</td>
<td>24.8</td>
<td>10</td>
<td>125 (1993)</td>
</tr>
<tr>
<td>Germany</td>
<td>25.3</td>
<td>8.6</td>
<td>34</td>
<td></td>
</tr>
<tr>
<td>France</td>
<td>17</td>
<td>7.1</td>
<td>42</td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td>36.5</td>
<td>26.4</td>
<td>72.2</td>
<td>1 800 5</td>
</tr>
<tr>
<td>Russia</td>
<td>60</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

World tendency: **Waste-to-Energy**

Combustion heat = 4200 - 7500 kJ/kg (brown coal - 10 400 kJ/kg)

Production of energy from SMW in the **USA**: 0.14 x 10^{12} MJ/year (1993)
2.10 x 10^{12} MJ/year (2010)

**Russia**: 14 combustion plants were built.

Currently just 2 modern plants using foreign equipment:
- in Moscow (150 thous.t/year)
- and in Cherepovets (1.7 t/h).
DISTRICT COMPLEX HEAT STATION: 40 thousand tons of solid municipal waste per year

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Tekhenergokhimprom, VNIPET

12 – rotating kiln; 15 – after-burner; 18 – steam boiler-utilizer; 28 – heat pumps

Project for Akademgorodok (2011)
Purpose: utilization/incineration of solid municipal, medical, and other toxic wastes; production of heat and syngas

- Project for Kuzbas Technology Business Center: «Plasma incineration of medical wastes»
- Project for China: Energy generation from agriculture wastes

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7. NONCONVENTIONAL ENERGY TECHNOLOGIES
Operation principle of the catalytic heating setup is based on catalytic combustion of fuels at temperature of 600 - 700 °C with simultaneous heat removal by introduction of heat-exchanging surfaces directly into the fluidized bed of a catalyst.
Technology of brown coal combustion in catalytic heating setup

Technology of Kansk-Achinsk coal combustion in the catalyst fluidized bed is developed. Cheap catalysts on the basis of slag are suggested.

Mechanochemical methods of suspension production with application of mills and pump-cavitators are suggested. Stable and steady burning compositions aimed at heavy oil substitution are obtained.

Nanodispersed organic-water-coal fuels

Combustion of mixture of coal, waste oil and water
BURNERS ON THE BASIS OF SOOT-VAPOR COMBUSTION

Novel combustion technology for nonconventional fuels with application of catalytic properties of soot nanoparticles

Autonomous burner of 20 kW

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Supercritical water (SCW) – active solvent for organic substances and oxygen (P > 22 MPa, T > 374°C)

SCW at T > 900 K hydrogenates conversion products

**Application:**
- Conversion of organic substances into liquid hydrocarbon fuel (LHCF)
- Combustion of organic substances with production of high-enthalpy actuating media for power installations.

**Organic substances:** coal, heavy oil residua, biological silt, sewage runoff

**Example of implementation in Novosibirsk:** while utilizing sewage runoff with a share of organic substances of 25%, a tube reactor with the volume of 39 liters will produce 70 kg/h of LHCF at utilization of 234 kg/h of sewage runoff. A bunch of 100 tubes with the area of 2.5 m² will produce 7 t/h of LHCF.

The scheme of installation for tar conversion in SCW at P = 30 MPa, T = 750°C.

Products: CH₄, C₂H₆, …

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**Initiation of fast ignition of volatiles inside coal matrix with application of new methods for concentration of SHF energy**

Concentrated impact of SHF energy (several GHz) on coal cobs leads to drastic heating (≈1000°C) inside coal, crack formation, fast devolatization and, hence, stable ignition.

*INITIAL STAGE OF HEATING OF A COAL LUMP WITH CRACKS AND THERMAL SHF RADIATION ON THEM (IR-RADIATION)*

**White color – cracks**

**Areas of IR irradiation**

*IT, INP, NSU*
CONCLUSIONS AND PROPOSALS

1. Priority development of coal power engineering in Russia for near future (in accordance with the world tendencies) with obligatory application of modern efficient and environmentally responsible technologies of combustion.

2. Radical growth in the share of fundamental and applied studies in the field of coal application, including:
   - deep investigation of solid fuel properties;
   - development of new types of fuels with improved operation, energy and ecology characteristics;
   - investigation of combustion processes (including flameless combustion), pyrolysis and gasification with consideration of catalytic phenomena and mechanical activation as well as application of various methods of control;
   - development of new methods for complex diagnostics with high spatial and time resolution;
   - development of reliable methods of numerical simulation for furnace processes with adaptation to engineering requirements.
3. Accelerated development of technologies for conversion of coal.

4. Development and practical application of technologies for utilization of solid municipal and industrial combustible wastes, especially, coal slags, with simultaneous production of heat and electricity.

5. Application of nonconventional approaches in coal power engineering, including micro-coal, water-coal fuel, plasma ignition, nanotechnologies, fuel elements, etc.

6. Organizational and financial support for development of coal theme:
   - centers of coal technologies
   - Federal program on clean coal power engineering
   - technological platforms
   - lots in the framework of activated Federal goal-oriented programs.