Analytical Solutions for Microwave Drying of Coal Fuel and its Applications

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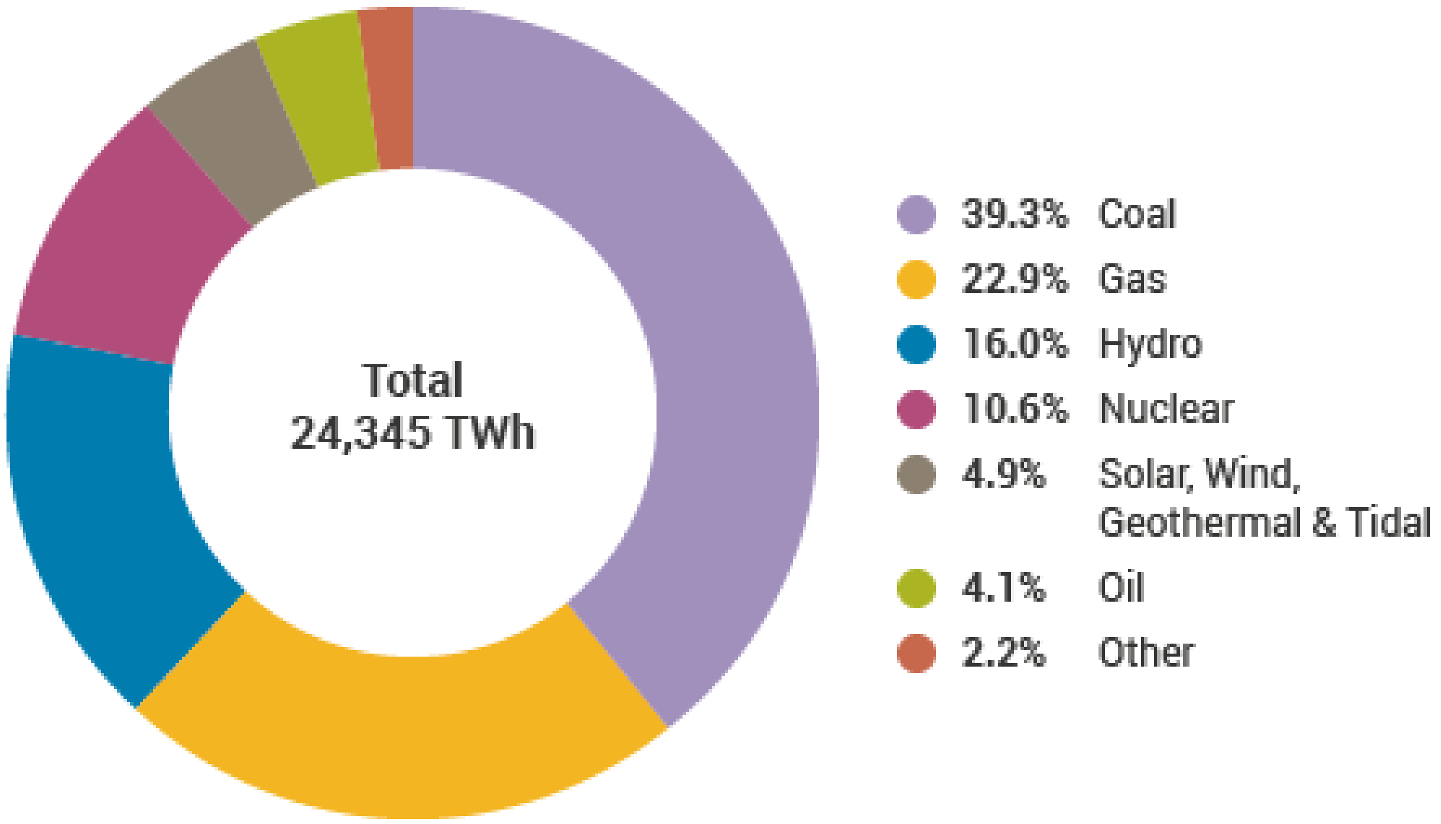
12th ECCRIA CONFERENCE
Cardiff University, Cardiff, UK.
5th-7th September 2018

Plan of the report

- Advantages and disadvantages of using coal fuel.
- Microwave treatment of coal.
- Modeling of the coal heating process.
- Modeling of coal drying.
- Conclusions.

World electricity generation by source



Source: IEA Electricity Information 2017

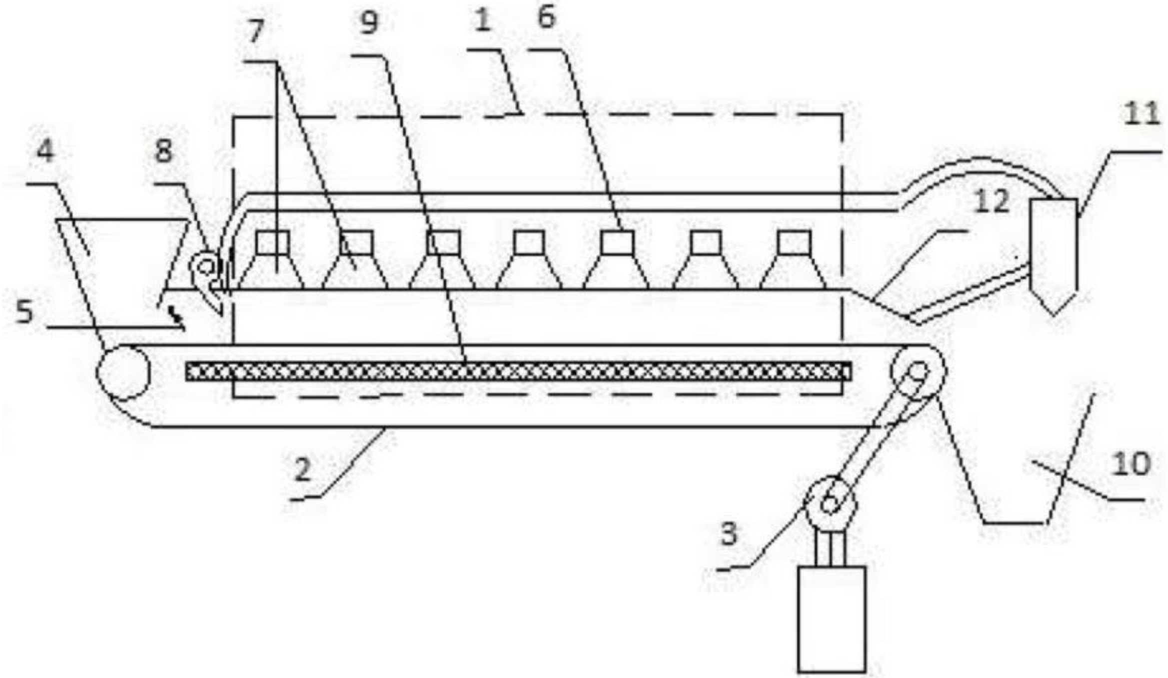
Advantages and disadvantages of using coal fuel.

1) Environmental Factor: Abundant emissions of gaseous (CO_2, NO_x, SO_x) and solid (ash) wastes
2) Energy factor: the efficiency of coal use is comparable, but still somewhat lower than primary energy resources.

1) Gas reserves are enough for ~ 60 years, oil ~ 40 years, and coal for ~ 500 years.
2) The prices for a coal resource are lower in comparison with analogues

Typical setup for microwave treatment for coal

- 1 - working chamber
- 2 - conveyor
- 3 - adjustable electric drive
- 4 - loading device
- 5 - adjustable slide gate
- 6 - magnetrons
- 7 - horn antennas
- 8 – fan
- 9 - absorbing material
- 10 - discharge device
- 11 - dust collecting device
- 12 - protective waveguide.



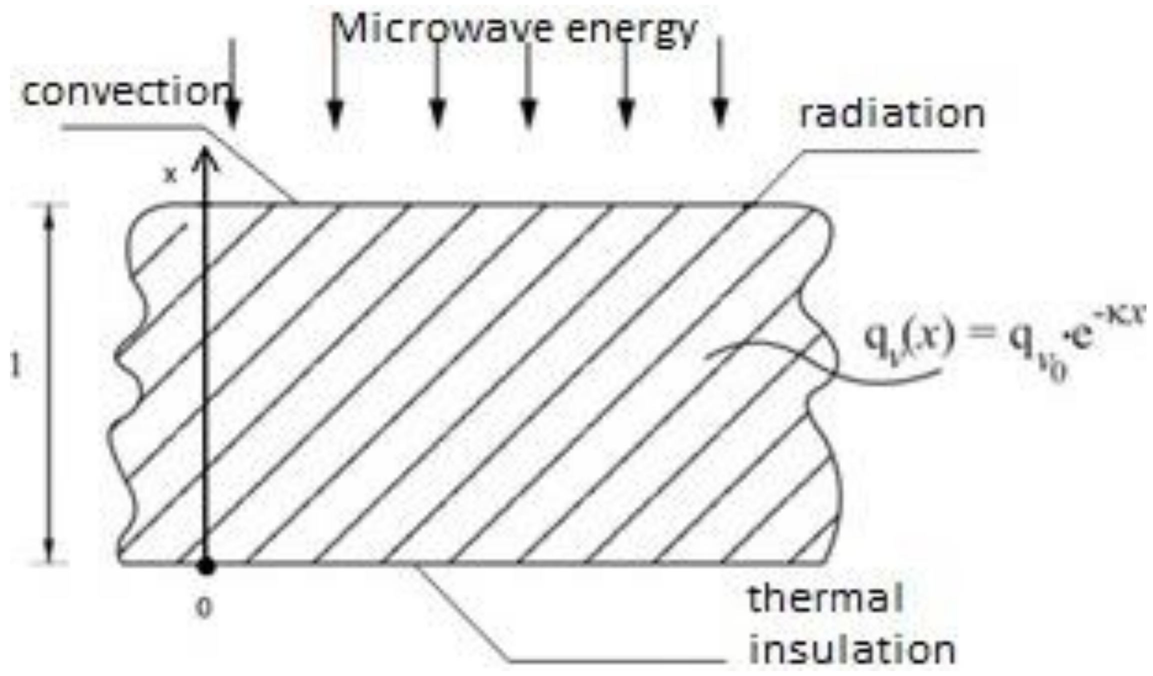
Benefits of using microwave treatment for coal

- Significant reduction in processing time
- Removal of harmful component
- Non-inertial process
- Volumetric impact

Reduction of harmful components in microwave treatment

- Complete removal of nitrogen
- Reducing the sulfur content by 50%
- Mercury by 50%
- Ash content is 30%
- Chlorine by 50%

Modeling of the coal heating process



$$\frac{\partial T(x,t)}{\partial t} = a\frac{\partial^2 T(x,t)}{\partial x^2} + \frac{q_{v_0}}{c\rho} e^{-kx}, \qquad (1)$$

$$0 \le t \le t_з,\ 0 \le x \le l,$$

$$T(x,0) = T_0, \qquad (2)$$

$$-\lambda \frac{\partial T(l,t)}{\partial x} = \sigma\left[T^4(l,t) - T_c{}^4\right] + \alpha\left[T(l,t) - T_c\right] \qquad (3)$$

$$\frac{\partial T(0,t)}{\partial x} = 0. \qquad (4)$$

Solution scheme

A system with a nonlinear boundary condition

Transition to dimensionless variables

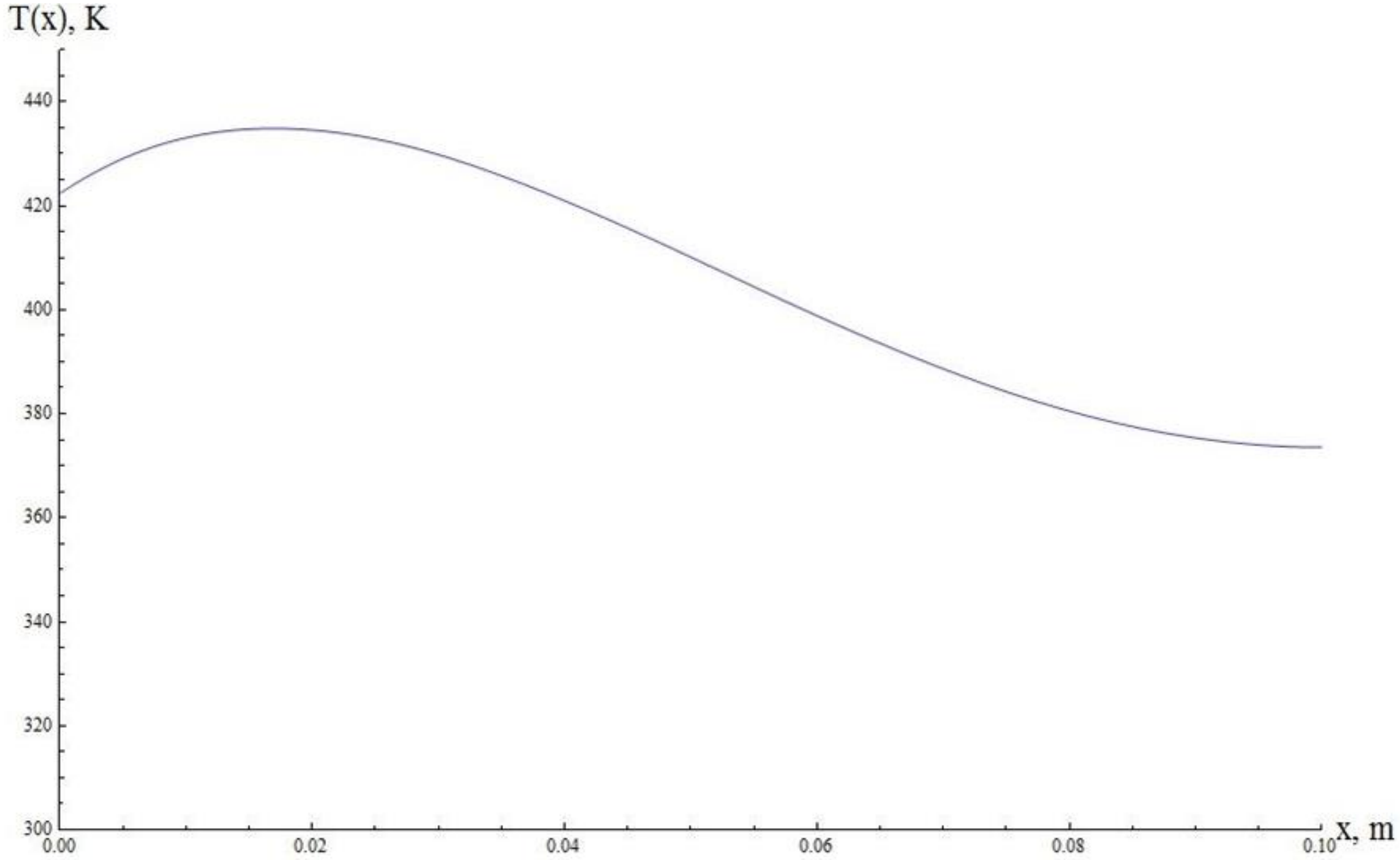
Integral Laplace transform, solution search in images:

$$\theta_L(X,s) = Ki_L(s)F_1(X,s) + Po_L(s)F_2(X,s)$$

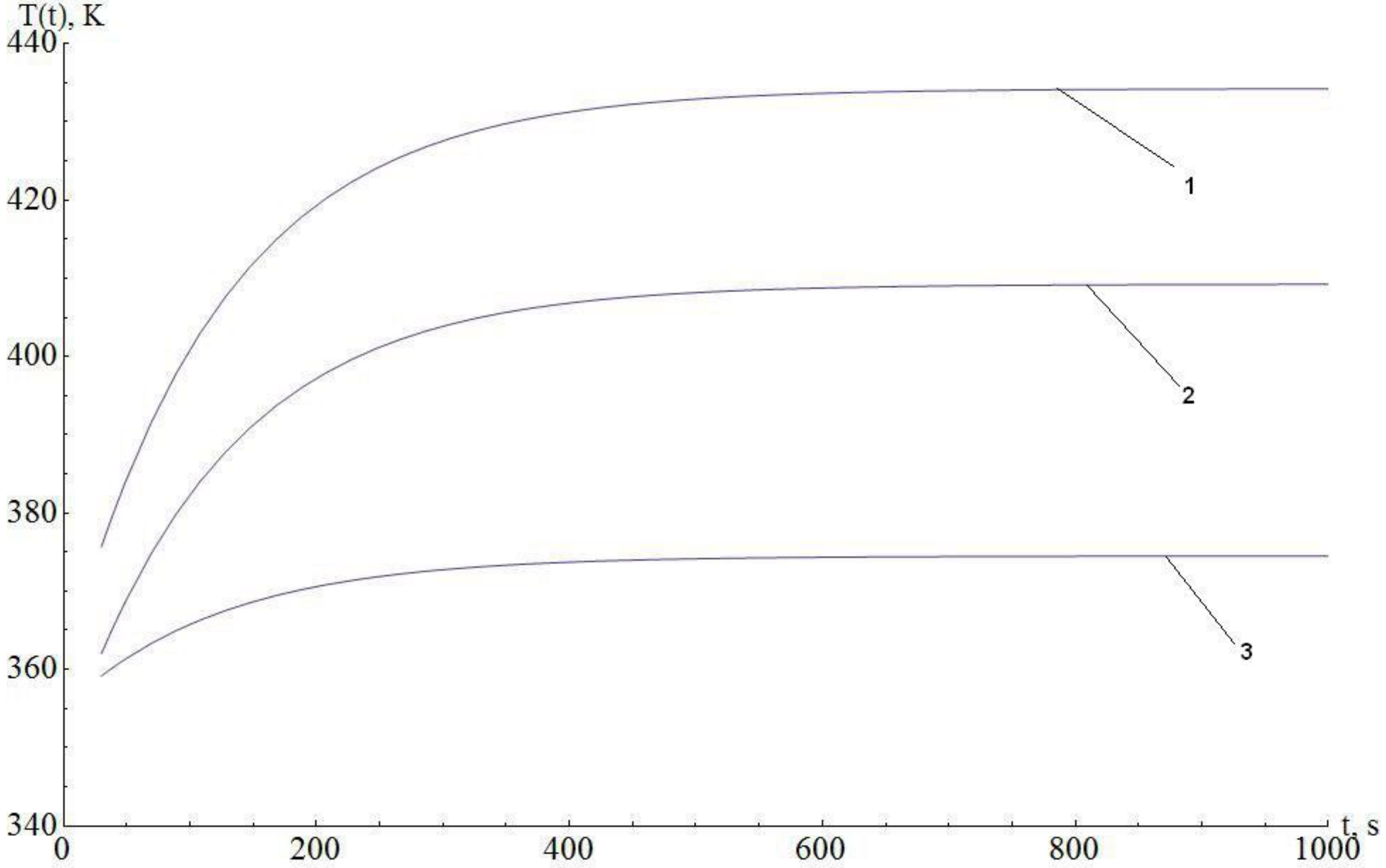
$$F_1(X,s) = -\frac{ch(\sqrt{s}X)}{\sqrt{s}\cdot sh(\sqrt{s})} \qquad F_2(X,s) = \frac{e^{-BuX}}{s(s-Bu^2)}$$

Search for asymptotic solutions for large and small time parameters

Depth distribution of temperature

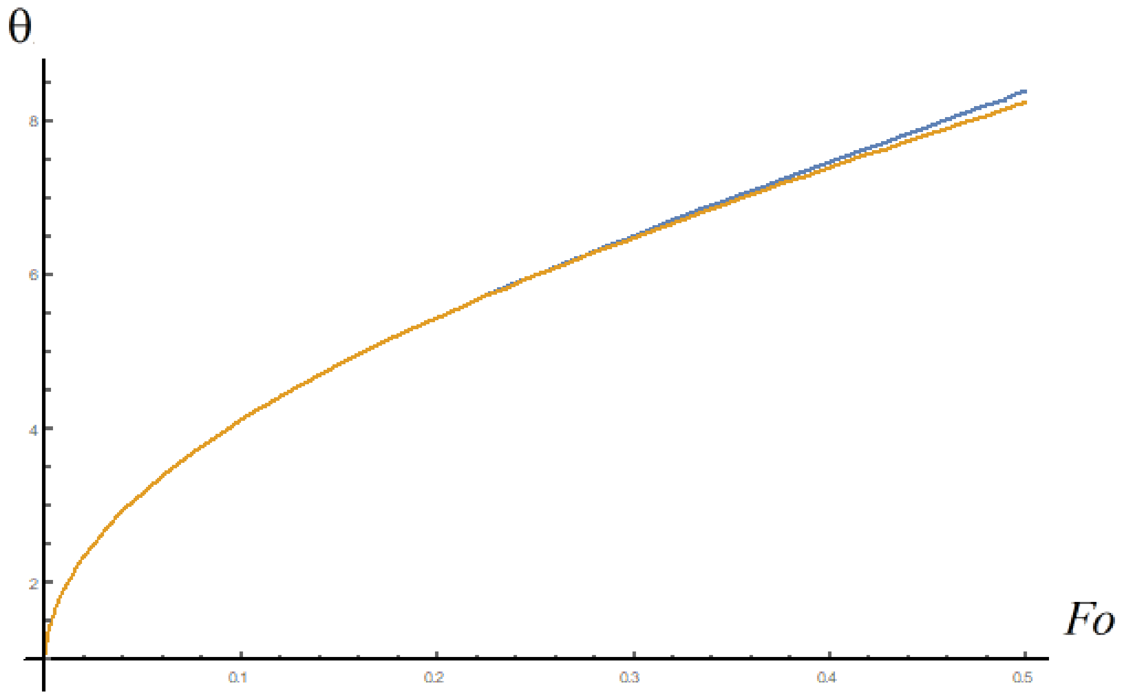


Temperature distribution over time



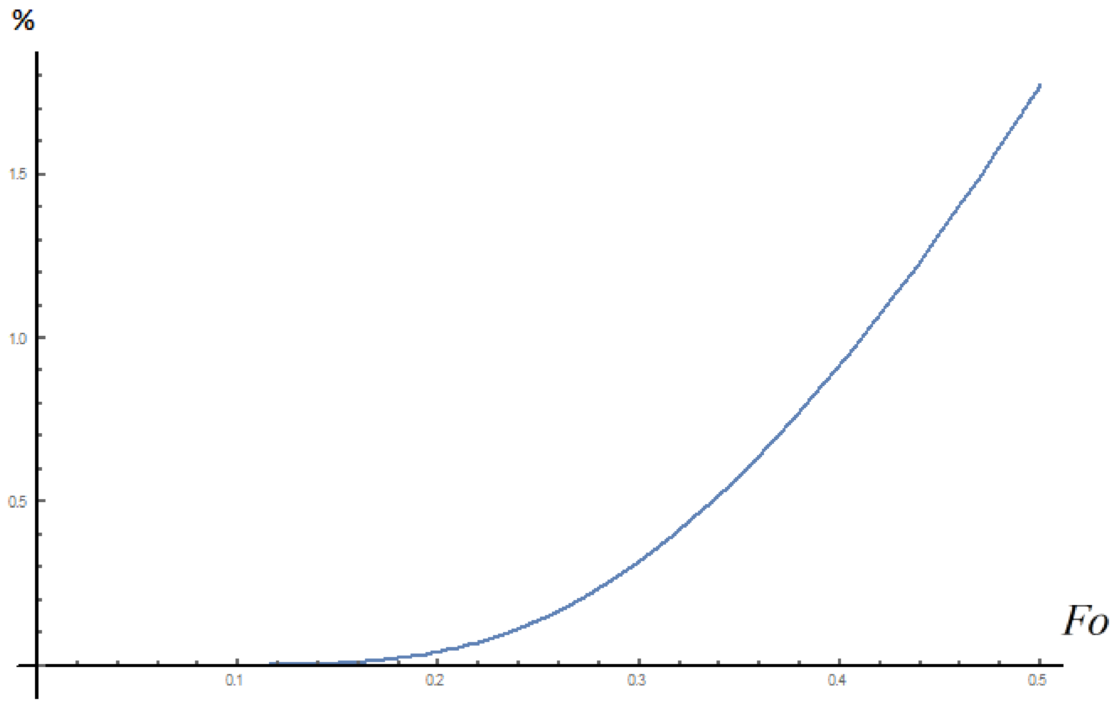
1 - maximum temperature in the layer
2 - temperature in the center
3 - temperature on the surface

Comparison of asymptotic solution with exact one for simple problem [A. V. Lykov] for small time parameters Fo

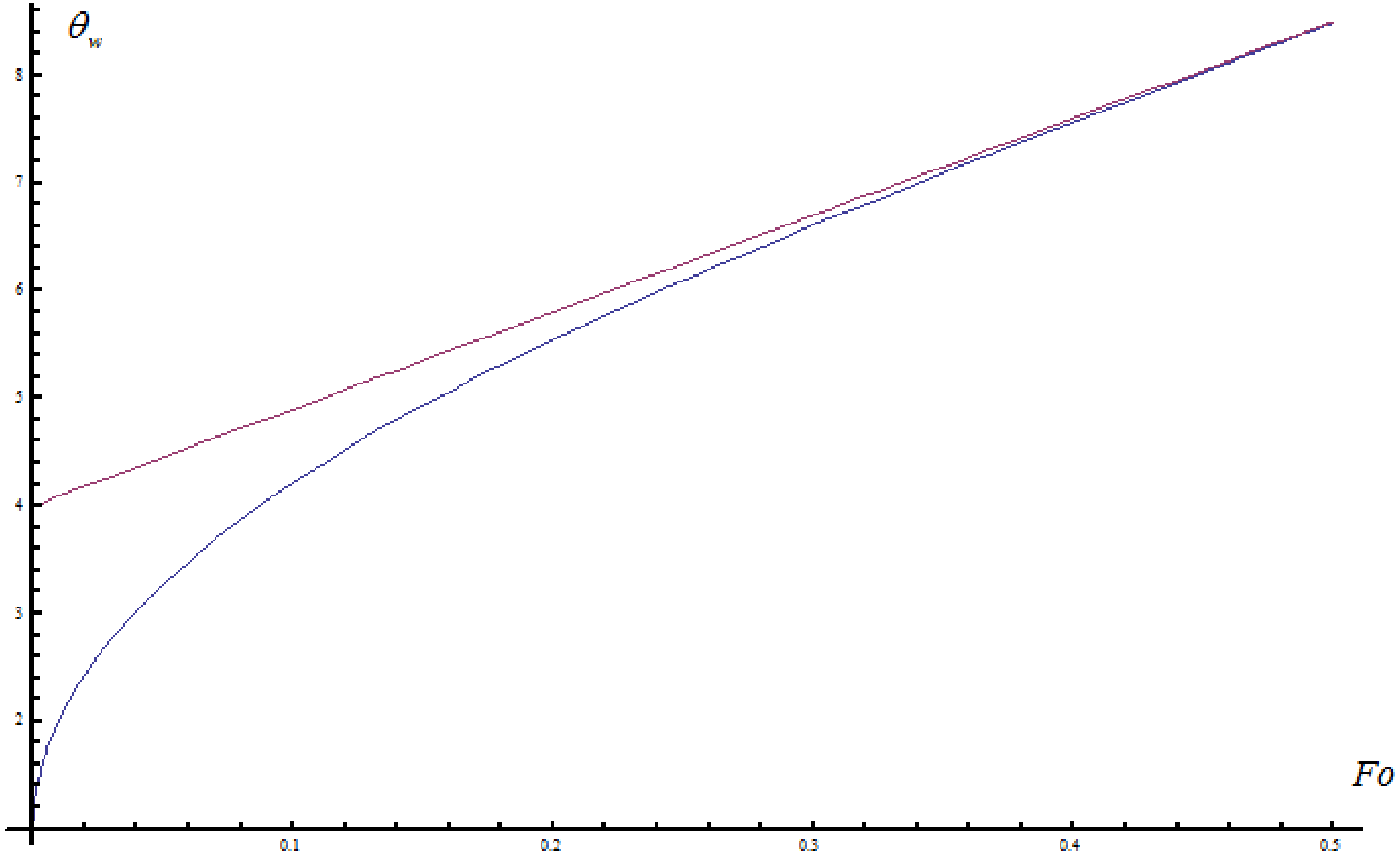


$$\Theta = \frac{T}{T_c}$$

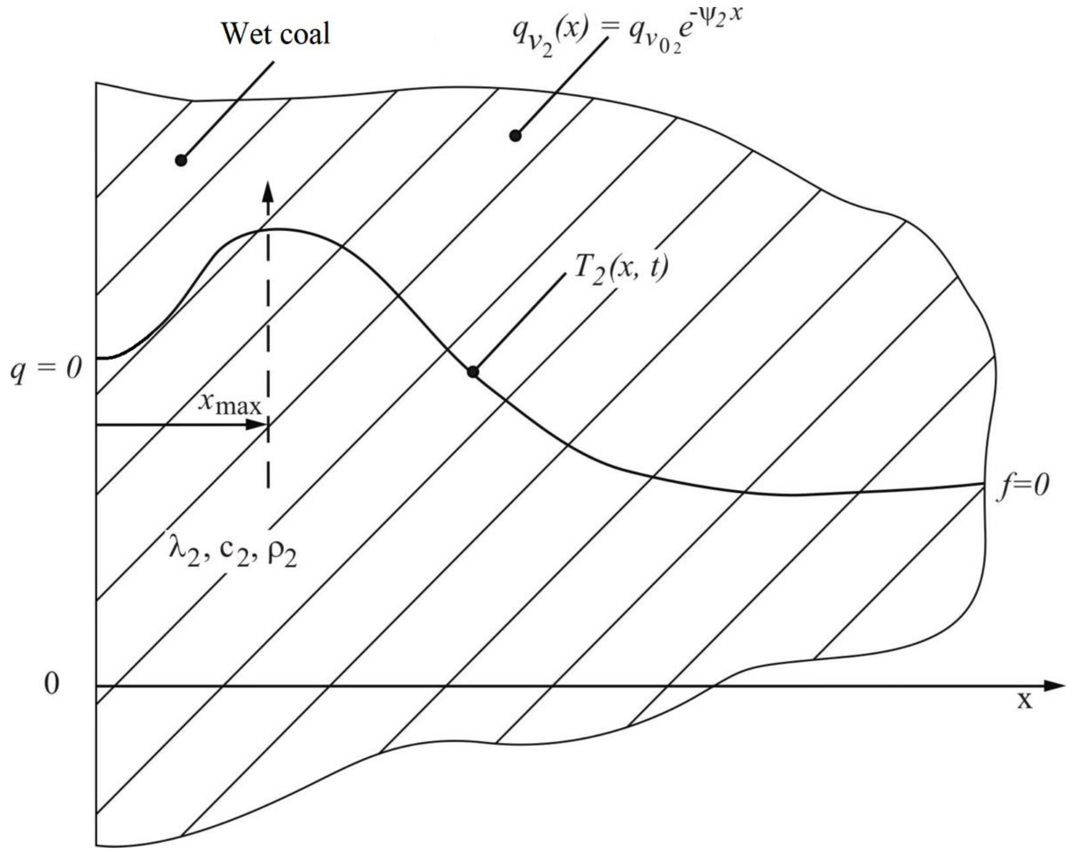
$$Fo = \frac{at}{l^2}$$

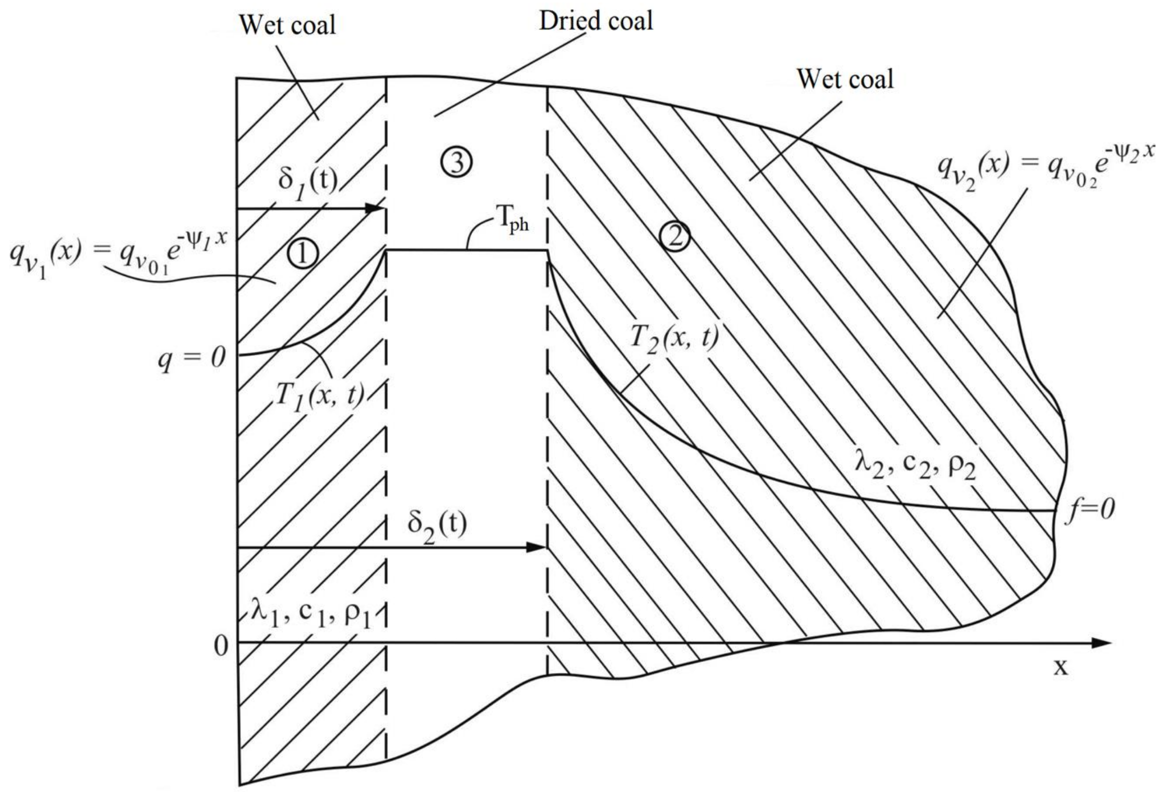


Comparison of asymptotic solution with exact one for simple problem [A. V. Lykov] for big time parameters Fo



Modeling of coal drying.





Equations for different drying zones of coal

$$\frac{\partial T_1(x,t)}{\partial t} = a_1 \frac{\partial^2 T_1(x,t)}{\partial x^2} + \frac{q_{\upsilon_O}}{c_1 \rho_1} e^{-\psi_1 x}$$

$$t > 0 \quad 0 < x < \delta_1$$

$$\frac{\partial T_1(0,t)}{\partial x} = 0$$

$$-\lambda_1 \frac{\partial T_1(\delta_1,t)}{\partial x} = \rho_1 H_{\text{и}} \frac{d\delta_1}{dt}$$

$T_1(x, 0) = \varphi_1(x)$

$T_1(\delta_1, t) = T_{\text{ф}}$

$$\frac{\partial T_2(x,t)}{\partial t} = a_2 \frac{\partial^2 T_2(x,t)}{\partial x^2} + \frac{q_{\upsilon_O}}{c_2 \rho_2} e^{-\psi_2 x}$$

$$t > 0 \qquad x > \delta_2$$

$$\frac{\partial T_2(\gamma_2,t)}{\partial x} = 0$$

$$-\lambda_2 \frac{\partial T_2(\delta_2,t)}{\partial x} = \rho_2 H_{\text{и}} \frac{d\delta_2}{dt}$$

$T_2(x, 0) = \varphi_2(x)$

$T_2(\delta_2, t) = T_{\text{ф}}$

The motion law of phase front for zone 1

$$t \cong D^{-1}\left[\frac{1}{2G}\ln\left|E-\delta_1 F+\delta_1^2 G\right|+\frac{F}{G}\frac{1}{\sqrt{4EG-F^2}}\,arctg\,\frac{2G\delta_1-F}{\sqrt{4EG-F^2}}\right]_{x_{\max}}^{\delta_1}$$

$$D=\frac{3\lambda_1}{\rho_1 H_1};\quad E=\frac{q_{v_{01}}}{\lambda_1 T_{\text{ф}}\psi_1^2}+\frac{H_1 x_{\max}}{c_1};\quad G=\frac{q_{v_{01}}}{2\lambda_1 T_{\text{ф}}\psi_1^2};\quad F=\frac{q_{v_{01}}}{\lambda_1 T_{\text{ф}}\psi_1^2}+\frac{H_1}{c_1}.$$

$$\delta_1(t)=2\varepsilon\sqrt{a_1 t}\ ,$$

$$\varepsilon=\sqrt{\frac{3m(m+2)}{m^2+9m+12}}\qquad m=\frac{c_1\,(T_{\text{ф}}-T_w)}{L_{\text{ф}}}$$

$$W_{\text{в}}(t)=\rho_{\text{в}}\left(\delta_{\max}-\delta_1(t)\right)+\rho_{\text{в}}\left(\delta_2(t)-\delta_{\max}\right)=$$

$$=\rho_{\text{в}}\left(\frac{1}{4P}\left(C_{L1}-C_{L2}\cdot t+4M^2\cdot t^2\right)-2\varepsilon\sqrt{a_1 t}\right)\qquad V=W_{\text{в}}'(t)=\rho_{\text{в}}\left(\frac{1}{4P}\left(C_{L2}+4M^2\cdot t\right)-\frac{2\varepsilon a_1}{2\sqrt{a_1 t}}\right)$$

Conclusions

- The task of microwave heating of wet coal was posed and solved analytically. Comparison with exact solutions showed high accuracy.
- On the basis of the solution for the heat-up stage, the problem of finding the microwave drying front for wet coal was posed and solved analytically. Comparisons were made with exact solutions.
- Expressions for the determination of moisture loss, calculation of time and drying rate are found.

Thank you!

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