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Heat transfer between hard ceramic particles and air plasma jet at multiphase flow in circular tube

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Ceramic fibre

Application in industry and environment protection:

- ✓ High-temperature insulation
- ✓ Noise insulation
- ✓ Filters
- ✓ Catalysts
- ✓ Reinforcement of concrete

Materials

Quartz

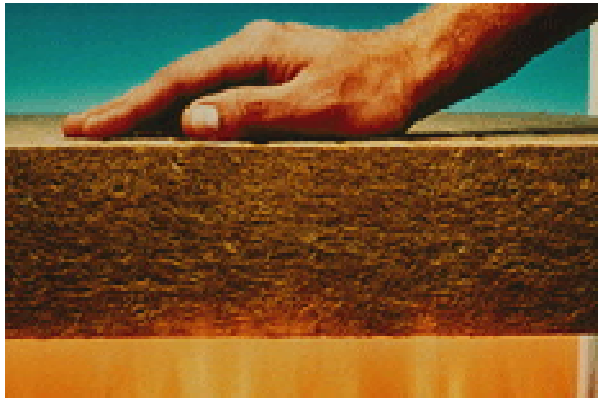
Dolomite

Zeolite

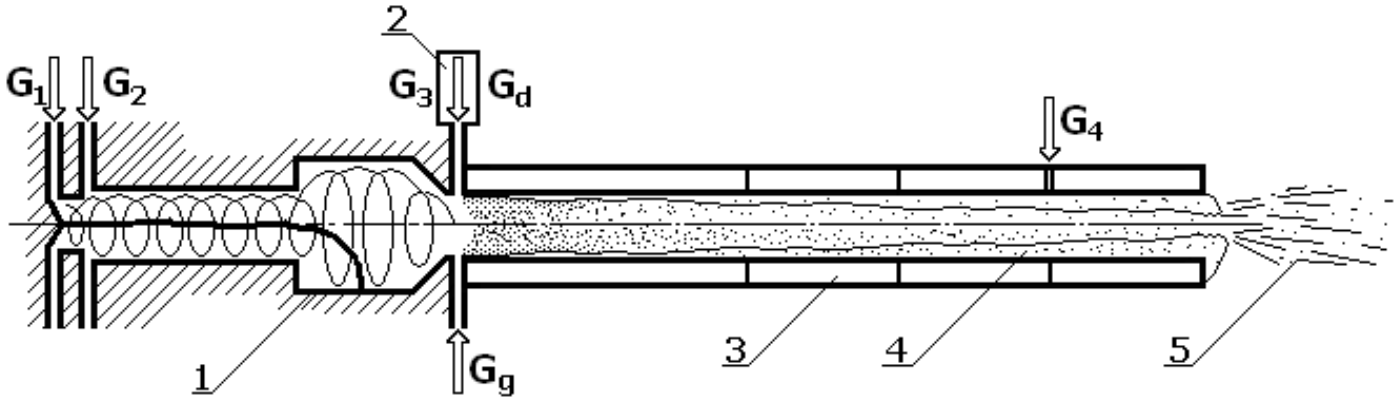
Basalt

Properties:

- ✓ High-temperature resistant
- ✓ Low thermal conductivity
- ✓ Chemical stability
- ✓ Low water absorption
- ✓ Eco-friendly and non-toxic
- ✓ Low price



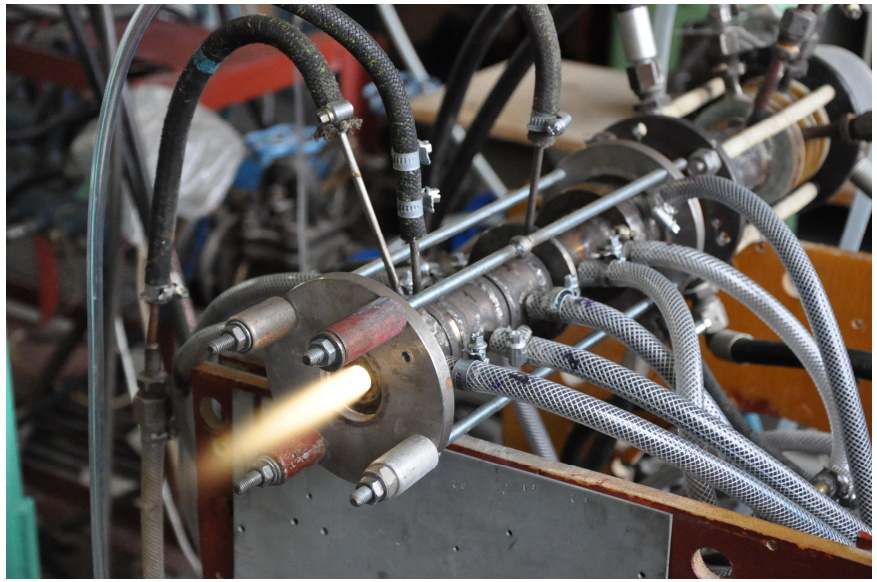
Experimental set-up



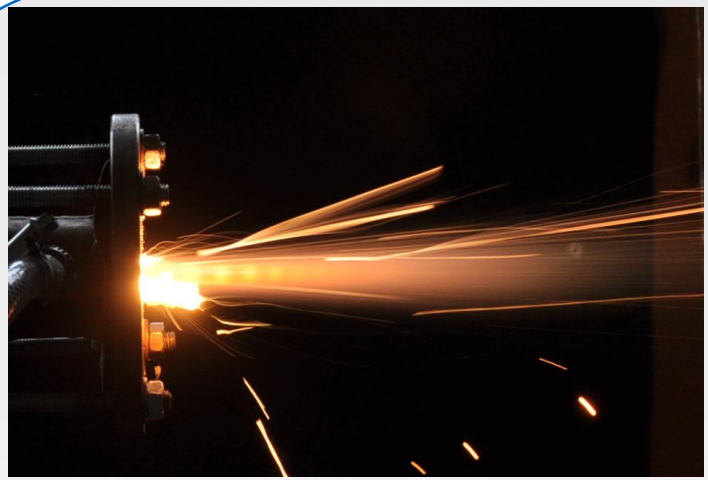
1 – plasma torch
2 – particle feeder
3 – section of the reactor
4 – melt flow
5 – fibre and granules

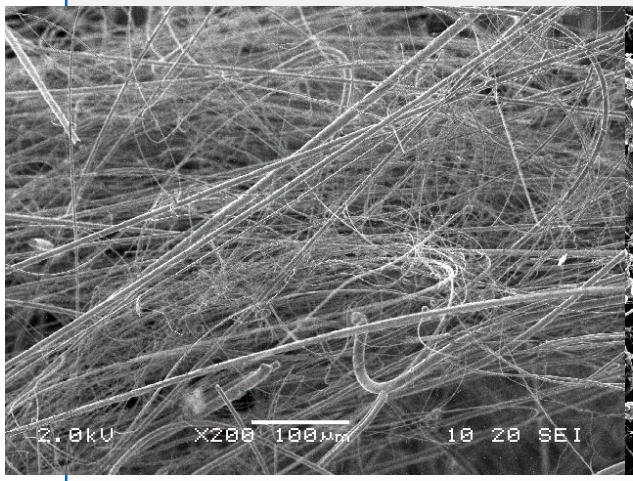
G_1 ir G_2 – plasma forming air flow,
G_3 – air and dispersive particles,
G_4 – additional air flow
G_g – propane gas.

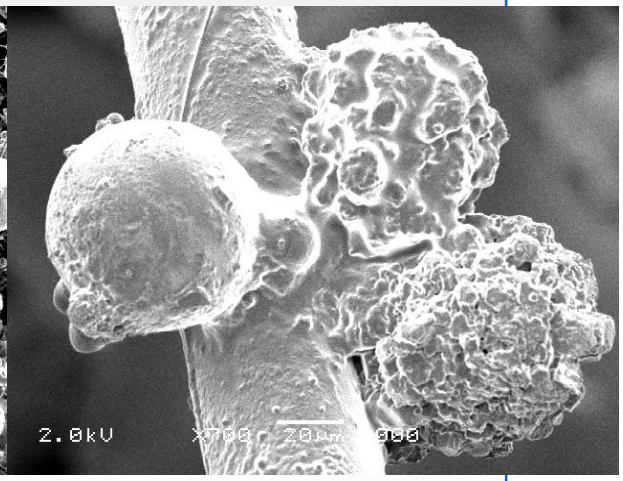
Plasma torch power, kW	50 – 120
Total air flow ($G_{1,2,3}$), 10^{-3} kg/s	9 – 41
Air flow at the cathode (G_1), 10^{-3} kg/s	1,7 – 1,8
Main air flow (G_2), 10^{-3} kg/s	7 – 24
Air flow for particle injection (G_3), 10^{-3} kg/s	1 – 9
Propane gas flow (G_g), 10^{-3} kg/s	iki 1,2
Dispersive particle flow (G_d), 10^{-3} kg/s	iki 6
Plasma flow temperature, no C_3H_8, K	1450 – 3600
Plasma flow temperature, with C_3H_8) K	1950 – 4300
Plasma flow velocity, m/s	400 – 1100



Plasma technology







Features:

- ✓ Higher temperatures available
- ✓ Melting and fibrillation of materials connected into one process
- ✓ Ability to determine the optimal conditions varying the temperatures in wide ranges
- ✓ Ability to stop the process and renew it immediately
- ✓ Obtained up to 300 nm thickness ceramic fibre

Measurements

- During the experiments:
  - The plasma torch current and voltage are measured;
  - Air and gas flow rates are measured;
  - The water flows for plasma torch and reactor cooling are weighted and their temperature differences are measured.

- Plasma torch power:

$$P = I \cdot U$$

- Heat losses to the cooling water:

$$Q_n = G_v \cdot \Delta t_v \cdot c_p$$

- Plasma flow heat:

$$Q_p = P - Q_n$$

- Nusselt number:

$$Nu_x = \frac{\alpha x}{\lambda_f}\left(\frac{T_f}{T_D}\right)^{0.9}$$

I – arc current
U – arc voltage
G_v – cooling water rate
Δt_v – cooling water temperature increase
c_p – specific heat of water
Q_d – added heat by propane combustion

- Average flow enthalpy:

$$H_f = \frac{Q}{G} + H_0 = \frac{P - \sum Q_n + Q_d}{G_0 + G_t + G_p} + H_0$$

- Heat transfer coefficient :

$$\alpha = \frac{Q_n}{F_n\left(T_f - T_w\right)}$$

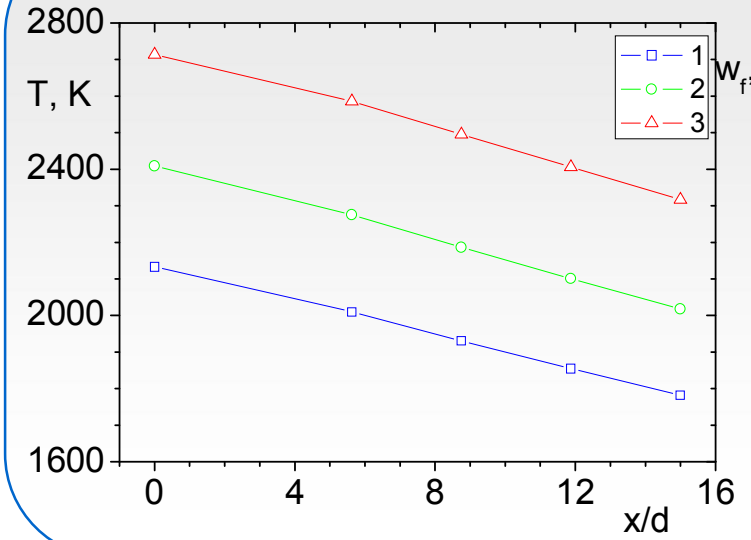
- Reynolds criterion:

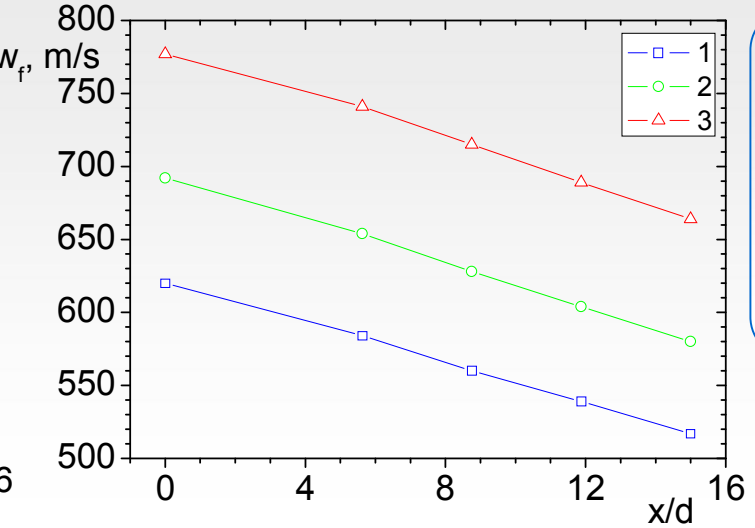
$$\mathrm{Re}_x = \frac{4Gx}{\pi d^2 \mu_f}$$

G_0 – plasma forming air flow
G_t – particles transporting air flow
G_p – additional air flow
F_n – inner surface area of the section
T_f – plasma flow temperature
T_w – temperature of reactor walls

Plasma flow temperature and velocity distribution (I)

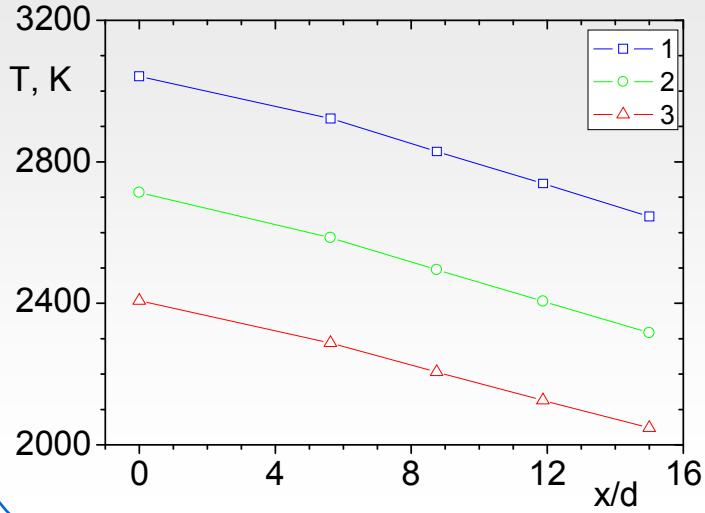
Dependence on PT power

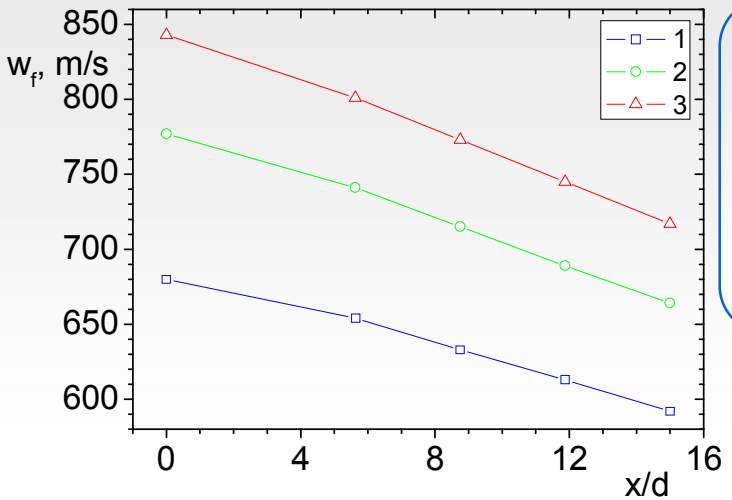




PT power:
1 – 56 kW
2 – 66 kW
3 – 81 kW
Air flow rate:
$20 \cdot 10^{-3}$ kg/s

Dependence on air flow rate

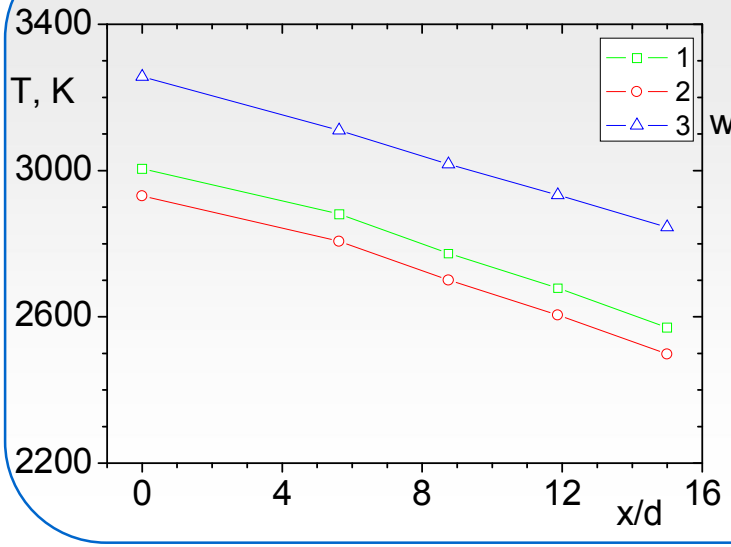


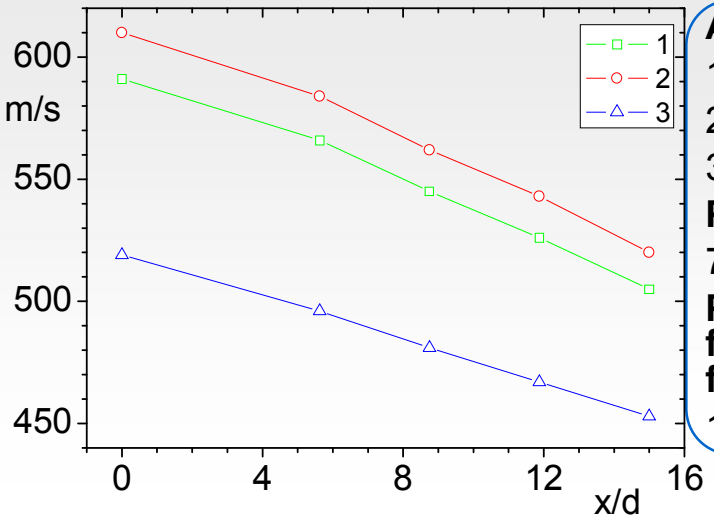


Air flow rate:
1 – $16 \cdot 10^{-3}$ kg/s
2 – $20 \cdot 10^{-3}$ kg/s
3 – $25 \cdot 10^{-3}$ kg/s
PT power:
81 kW

Plasma flow temperature and velocity distribution (II)

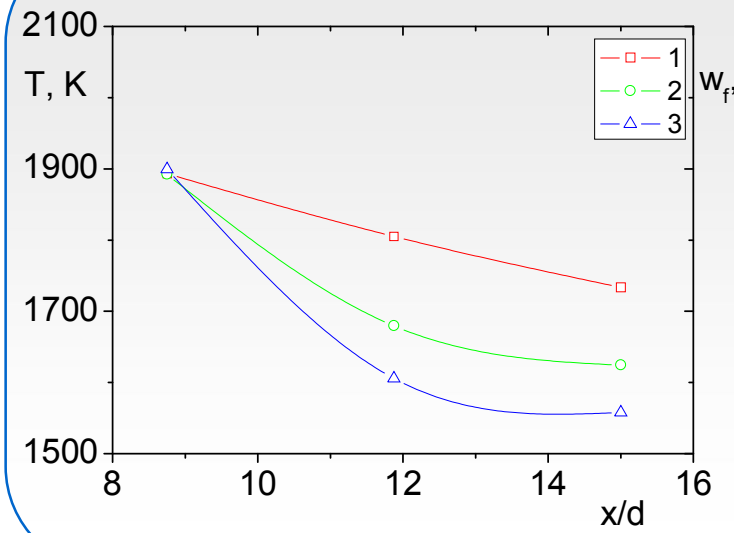
Dependence on dispersive particle transporting air flow

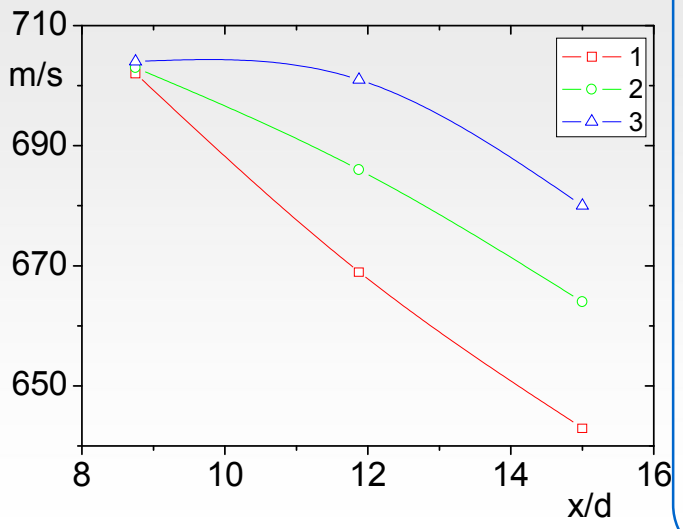




Air flow rate:
1 – $2 \cdot 10^{-3}$ kg/s
2 – $3 \cdot 10^{-3}$ kg/s
3 – no flow
PT power:
70 kW
Plasma forming air flow rate:
$11 \cdot 10^{-3}$ kg/s

Dependence on additional air flow

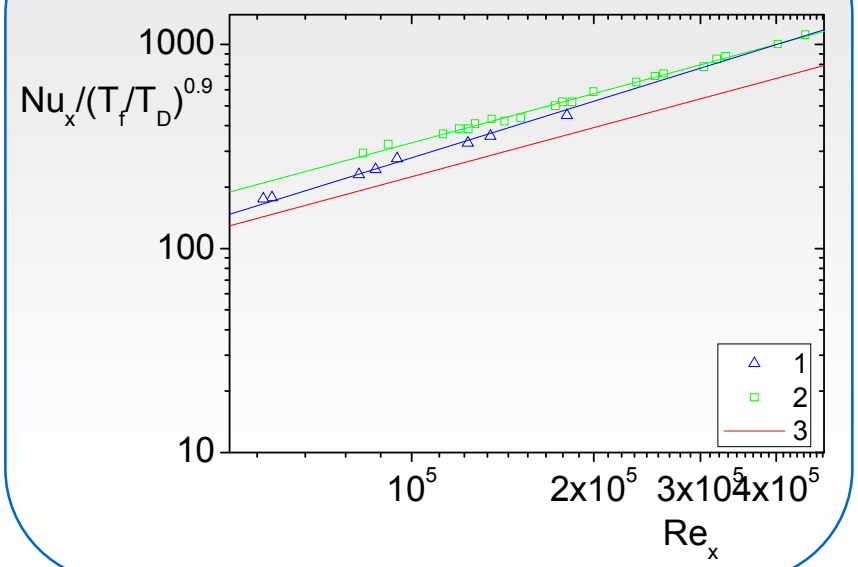




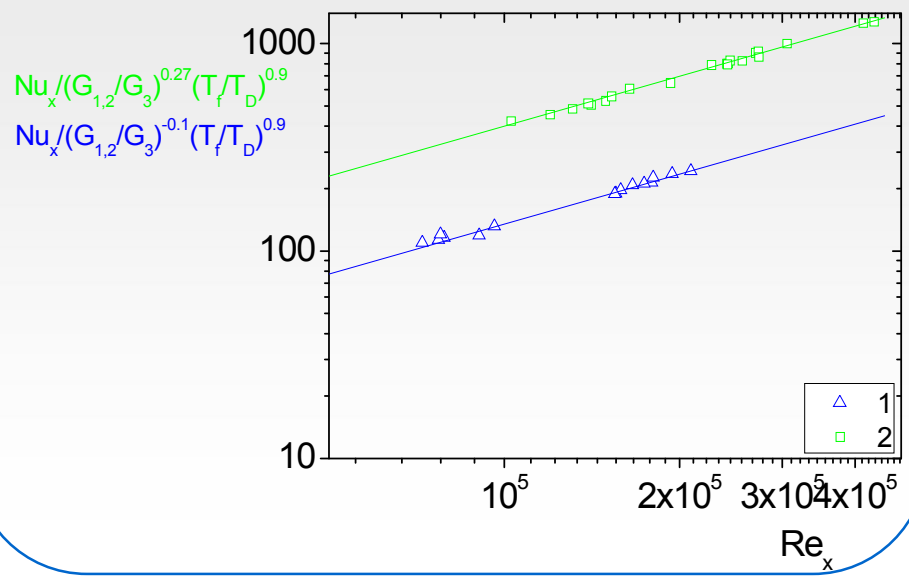
Air flow rate:
1 – no flow
2 – $3 \cdot 10^{-3}$ kg/s
3 – $5 \cdot 10^{-3}$ kg/s
PT power:
71 kW
Plasma forming air flow rate:
$18 \cdot 10^{-3}$ kg/s
Particle transporting air flow rate:
$8 \cdot 10^{-3}$ kg/s

Generalized heat transfer

No additional gases



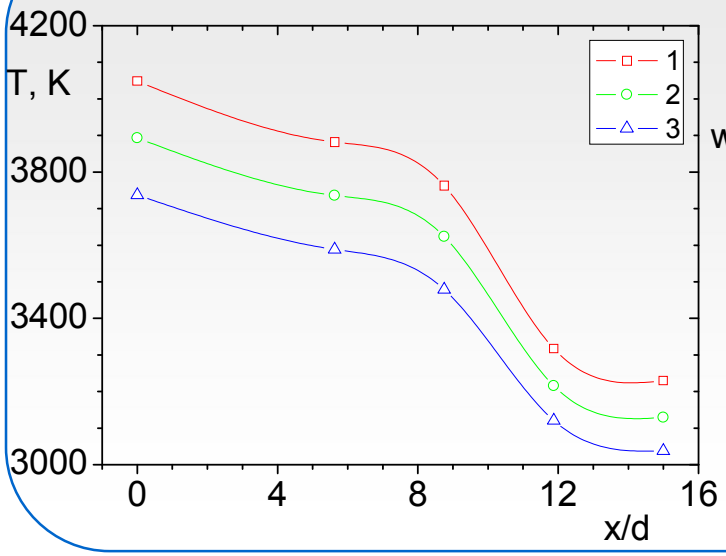
With particle transporting air flow

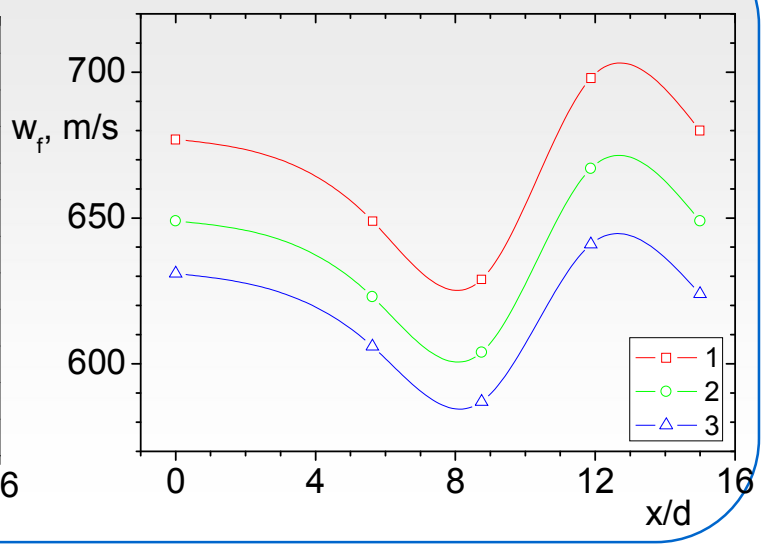


1. Reactor length, x/d≤5,6	$Nu_x = 7 \cdot 10^{-3}\,\mathrm{Re}_x^{0,92}\left(\frac{T_f}{T_D}\right)^{0,9}$	$Nu_x = 13{,}5 \cdot 10^{-3}\,\mathrm{Re}_x^{0,8}\left(\frac{G_{1,2}}{G_3}\right)^{0,27}\left(\frac{T_f}{T_D}\right)^{0,9}$
2. Reactor length, x/d>5,6	$Nu_x = 33 \cdot 10^{-3}\,\mathrm{Re}_x^{0,8}\left(\frac{T_f}{T_D}\right)^{0,9}$	$Nu_x = 40 \cdot 10^{-3}\,\mathrm{Re}_x^{0,8}\left(\frac{G_{1,2}}{G_3}\right)^{-0,1}\left(\frac{T_f}{T_D}\right)^{0,9}$
3. High-temperature stabilized flow equation	$Nu_x = 25.5 \cdot 10^{-3}\,\mathrm{Re}_x^{0,8}\left(\frac{T_f}{T_D}\right)^{0,9}$	

Addition of propane gas flow

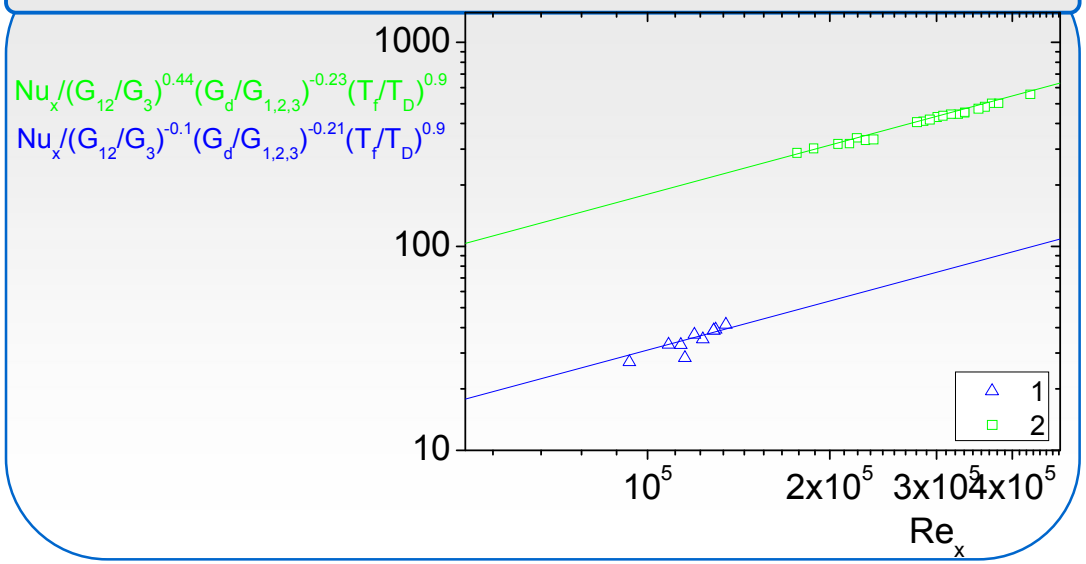
Plasma flow temperature and velocity distribution





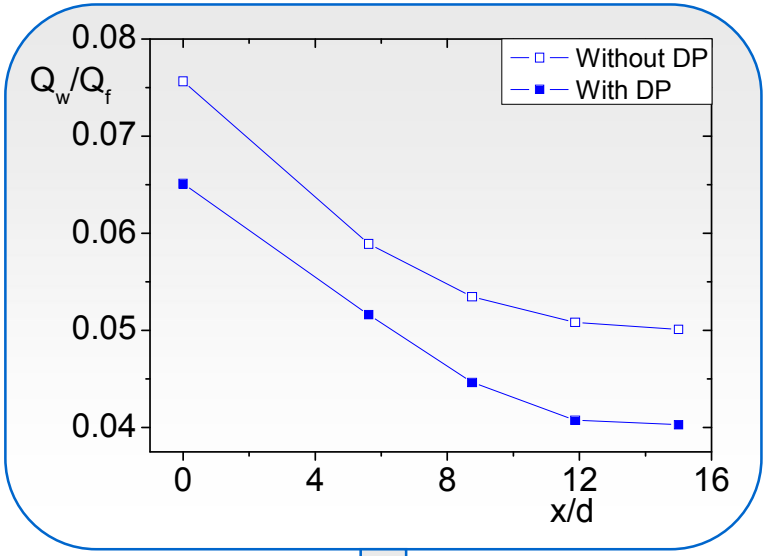
Propane gas flow:
1 – $0{,}8\cdot10^{-3}$ kg/s
2 – $0{,}65\cdot10^{-3}$ kg/s
3 – $0{,}5\cdot10^{-3}$ kg/s
PT power: 70 kW
Plasma forming air flow rate:
$11\cdot10^{-3}$ kg/s
Particle transporting air flow rate:
$1\cdot10^{-3}$ kg/s
Additional air flow rate:
$3\cdot10^{-3}$ kg/s

Generalized heat transfer



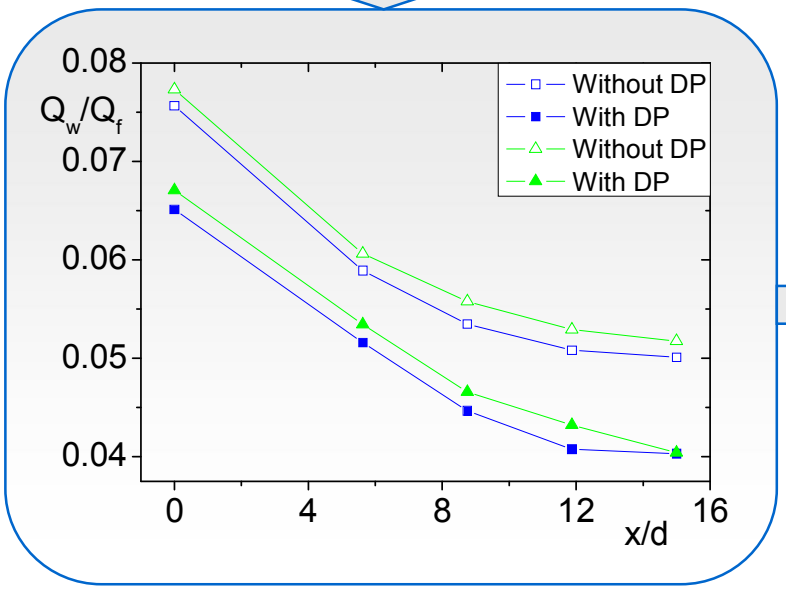
1. Reactor length, x/d≤5,6
$Nu_x = 2{,}3\cdot10^{-3}\,\mathrm{Re}_x^{0{,}8}\left(\frac{G_{1,2}}{G_3}\right)^{0{,}44}\left(\frac{G_d}{G_{1,2,3}}\right)^{-0{,}23}\left(\frac{T_f}{T_D}\right)^{0{,}9}$
2. Reactor length, x/d>5,6
$Nu_x = 18\cdot10^{-3}\,\mathrm{Re}_x^{0{,}8}\left(\frac{G_{1,2}}{G_3}\right)^{-0{,}1}\left(\frac{G_d}{G_{1,2,3}}\right)^{-0{,}21}\left(\frac{T_f}{T_D}\right)^{0{,}9}$

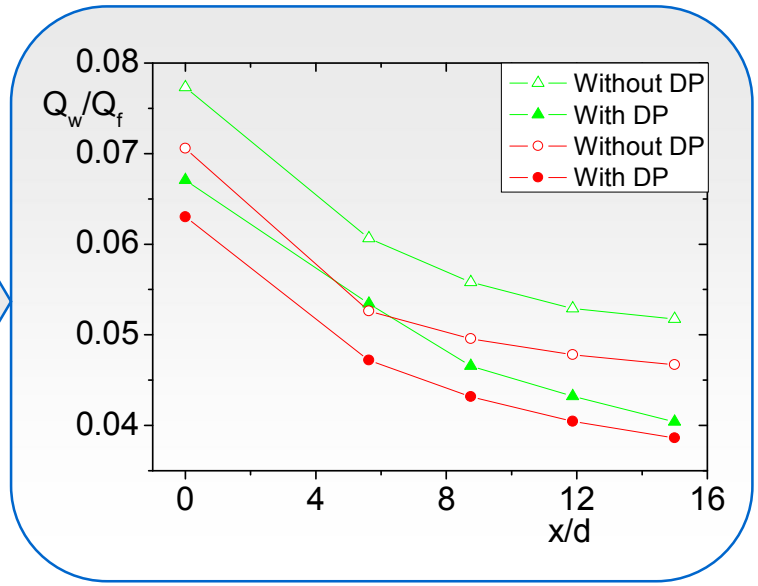
Interaction between plasma flow and dispersive particles



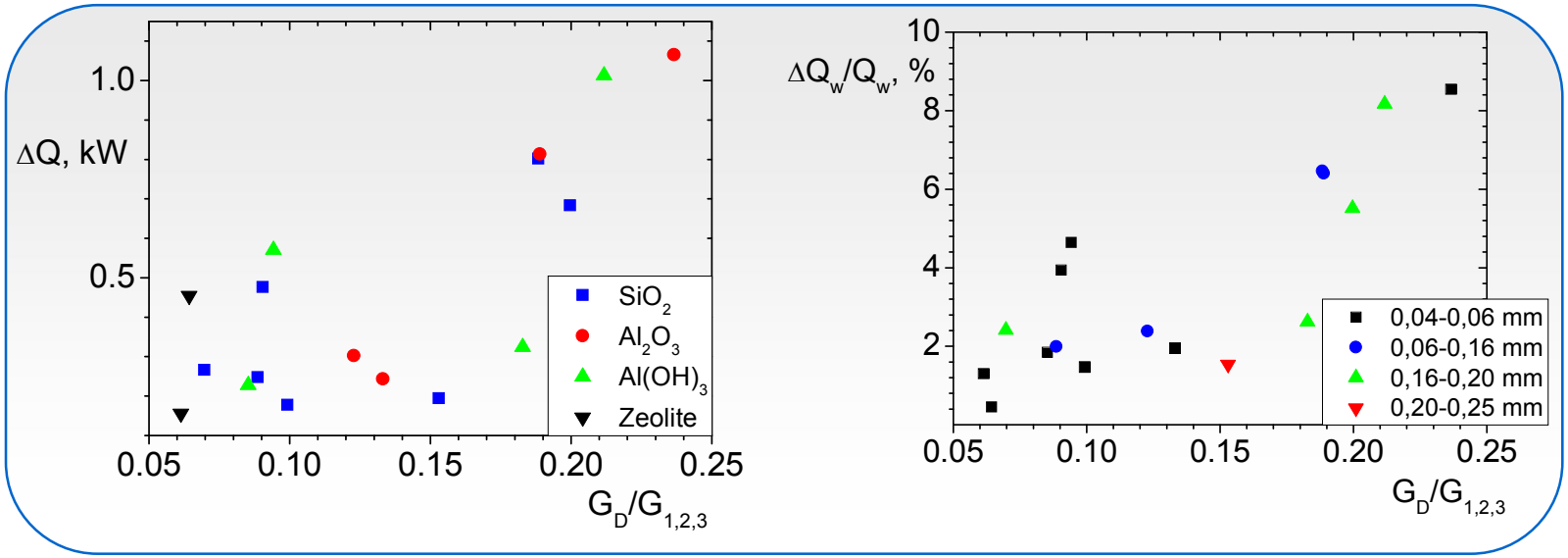
Al_2O_3
3,3 g/s
0,04 – 0,06 mm

P, kW	53	62	62
$G_{1,2}$, g/s	12	12	16
G_3, g/s	1,5	1,5	1,5

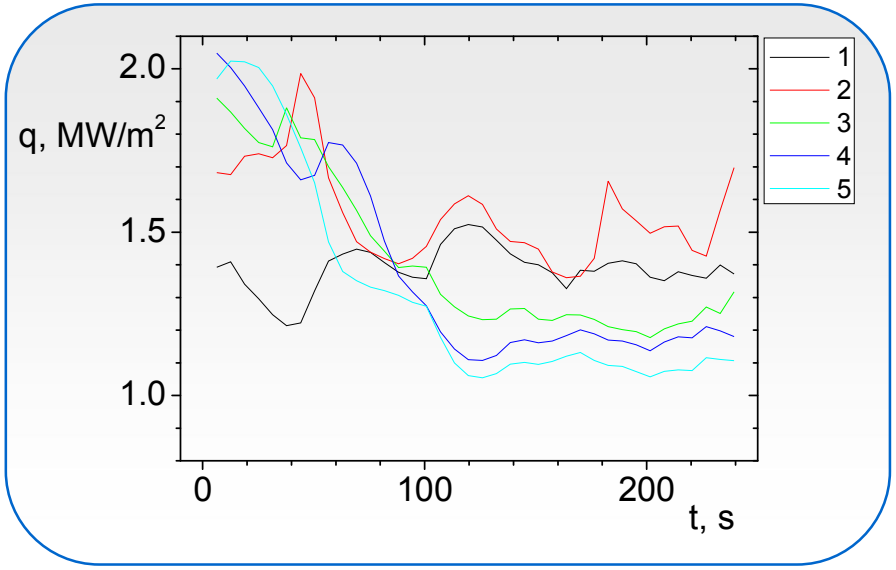




Interaction between plasma flow and dispersive particles



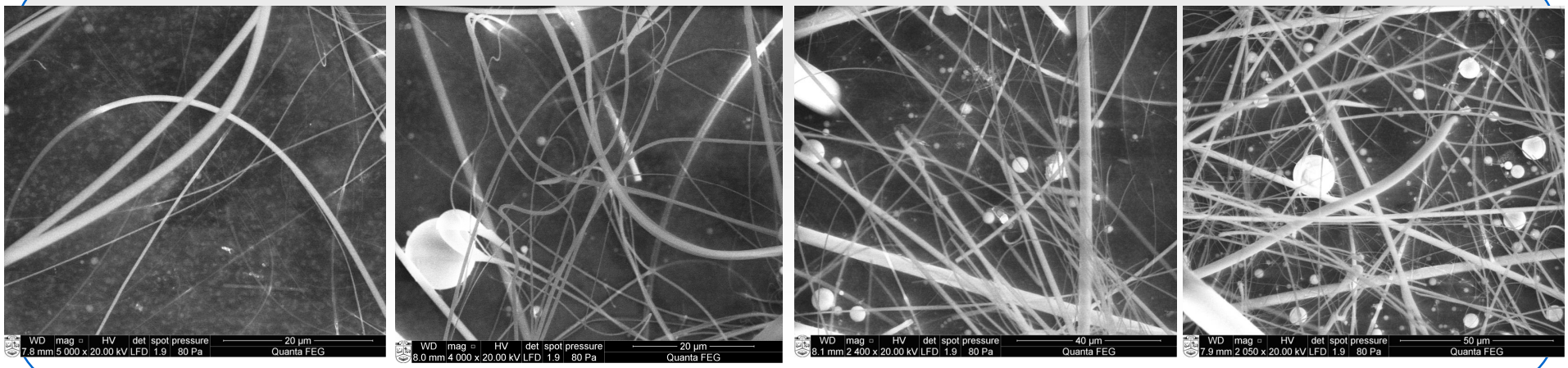
P, kW	G_{12}, g/s	G_3, g/s
65	16	1,6



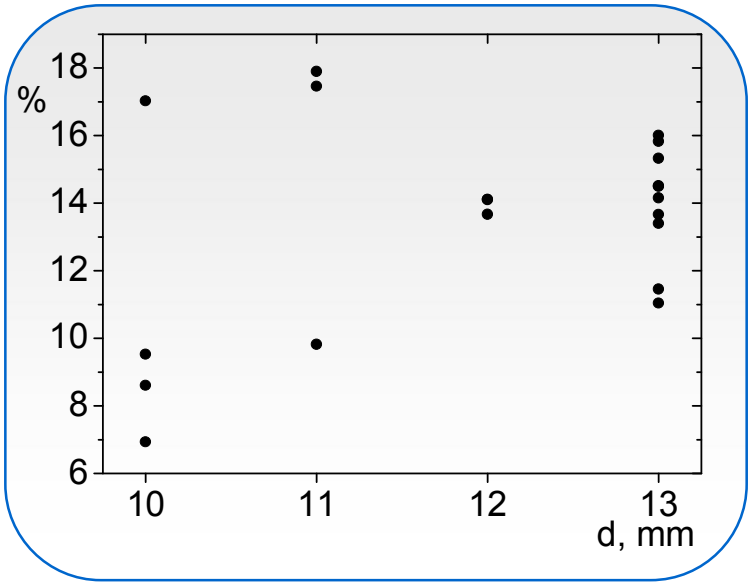
P, kW	G_{12}, g/s	G_3, g/s	G_d, g/s
78	12	1	0.8

Zeolite
1,2 g/s
0,04 – 0,06 mm

The outlet nozzle influence



Outlet nozzle diameter (m)	0,010	0,011	0,013	0,015
PT power (kW)	78	80	81	83
Air flow rate (g/s)	15	18	16	17
Particles transporting air (g/s)	5	5	5	5
Additional air flow rate (g/s)	2	2	2	2
Propane gas flow rate (g/s)	0,8	0,9	0,8	0,8
Flow temperature (K)	2080	2300	2760	2920
Flow velocity (m/s)	1520	1410	1260	980



Conclusions

- The experimental measurements show that after injection of constant flow of dispersed particles into the reactor, the heat transfer intensity to the reactor wall decreases by 10-20 %, depending on the parameters of the plasma torch. Increasing plasma torch power, the heat transfer intensity to the dispersive particles decreases at reactor distances $x/d<8.8$ and increases at the distances of $x/d\geq8.8$. With the increase of plasma forming air flow rate, the heat transfer to the dispersed particles decreases in the entire length of the reactor, and especially at the distances of $x/d\geq8.8$.
- It was observed that the intensity of heat transfer between the plasma flow and dispersed particles increases as the mass concentration of particles in the plasma flow increases and the particle size decreases. The increase of mass concentration of cold dispersive particles in the plasma flow from 6 to 24 % causes the decrease of the heat flux to the reactor walls from 6 to 31 %, due to intensive heat transfer from plasma flow to the particles. The elemental composition of dispersed particles used in this work has no influence on the heat transfer.
- The experimental realization of the melting and fibrillation process showed that the increase of the velocity of leaving the reactor plasma flow by 60 % increases the productivity of the derived fiber by 5 %, and decreases the diameter of fiber filaments, as well as the amount of granules in the fiber.

Thank You!

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