UDC 536.2:533.9

EXPERIMENTAL RESEARCH ON HEAT TRANSFER DURING TURBULENT MULTI-PHASE PLASMA FLOW IN CIRCULAR TUBE

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Abstract

One of the most important processes taking place during ceramic material fibrillation in plasma-chemical reactor which makes the fibre formation successful is the heat transfer between multi-phase plasma flow which consists of plasma flow and melted dispersive raw material. However, the heat loss to the reactor walls takes place too. The control of heat flux from the plasma flow to the dispersive material and heat loses to the reactor walls becomes the most important issue to optimize the fibrillation process. In this work the heat transfer to the plasma-chemical reactor walls was experimentally investigated and its dependence on plasma flow parameters was generalized with and without presence of dispersive material in the reactor channel.

It was found that the heat transfer in the plasma-chemical reactor can be described using turbulent flow equations. The values of heat transfer results obtained in this work are in good agreement with the classical case. The amount of heat transfer decrease in the reactor channel conditioned by additional gas and dispersive particles flows was measured.

Introduction

The processing of dispersive ceramic materials employing plasma technology is related with intensive heat transfer between high-temperature plasma flow, dispersive particles and the environment. Application of plasma technology in the case of mineral fibre production in order to improve quality of final product and efficiency of plasma spraying process requires significant reduction of heat loss to the reactor walls and increase of the interaction time between plasma flow and dispersive particles. The research on heat transfer between the walls of circular tube and multi-phase flow consisting of plasma, solid, partly melted and fully melted dispersive ceramic particles is very challenging but complicated because of a lot of different processes which takes place in plasma environment, including exothermic and endothermic reactions, dissociation, ionization, the surface erosion and etc [1].

Since heat transfer plays an important role in melting of ceramic materials and production of ceramic fibres, it is desirable to have a quantitative understanding of the heat flow processes occurring in the plasma jet reactors. Therefore, this paper is devoted for investigation of the heat transfer between cold walls of the plasma-chemical reactor and multi-phase plasma flow with ceramic particles. Heat transfer between plasma flow and ceramic particles was investigated experimentally and generalized.

The methodology

The experiments were performed with a plasma-chemical reactor applied for fibrillation of raw ceramic materials. It was developed in Plasma Processing Laboratory of Lithuanian Energy Institute. The plasma-chemical reactor (Fig. 1) consists of plasma torch 50-120 kW of power. 0.29 m. length circular channel made of stainless steel is connected to the exhaust nozzle of the plasma torch.

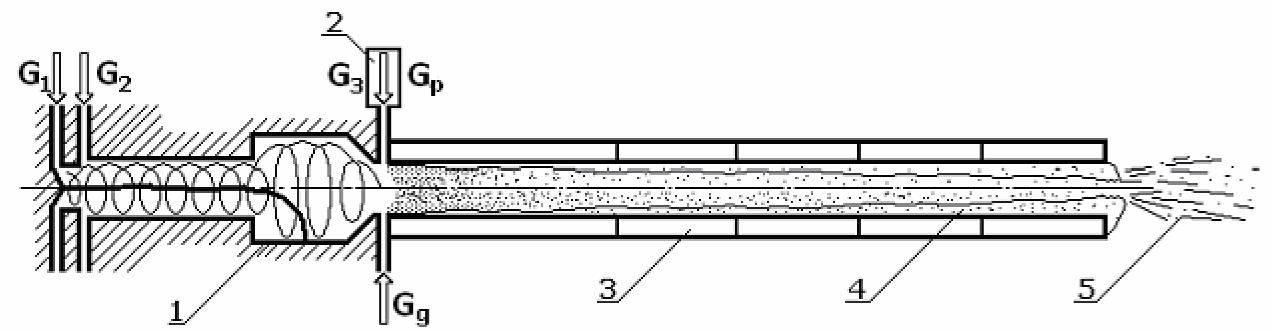


Fig. 1. Plasma-chemical reactor: 1 – plasma torch, 2 – feeding of dispersive particles, 3 – section of the reactor, 4 – melt flow, 5 – fibre and granules

The experimental channel of the plasma-chemical reactor consists of five sections. The internal diameter of each section is 0.016 m. The length of the first section connected to the plasma torch is 0.09 m, and other four sections are 0.05 m of length. All sections are cooled by water and insulated from each other, so no significant heat transfer between the cooling water of each section occurs.

Air was used as plasma forming and dispersive particles carrying gas. Air plasma is optically thin and heat transfer by radiation in such media is negligible. To increase the heat transfer between plasma flow and dispersed particles by radiation the propane gas was added to the plasma flow in the beginning of the reactor.

The electric arc ignited in the plasma torch heats up and ionizes the air flow flowing through the reactor with the flow rate of (G_1+G_2). Up to 3400 K heated air flow up to $35 \cdot 10^{-3}$ kg/s of rate enters the reactor channel. At the entrance of the reactor the additional flows – the dispersed particles (G_p) and them carrying air (G_3) and propane gas (G_g) flows – are injected into the reactor. The propane gas ignites and burns, the dispersed particles carrying air heats up and mixes with plasma flow and the dispersed particles starts to melt. The melting of dispersed particles forms a melt flow which due to high plasma flow velocity sticks to the reactor walls and flows along the plasma flow direction until it reaches the outlet of the reactor. In the outlet of the reactor the melt viscosity is high enough that kinetic energy of plasma flow is able to disturb the melt surface and pull of elementary jets from melt waves and droplets, which are then cooled and solidified.

During the experiments the plasma torch arc current and voltage, air and gas flow rates, plasma torch and reactor walls cooling water flow rates and their temperature differences are measured. The raw dispersed particles were weighted before the start and at the end of experiments.

Plasma flow velocity and temperature, heat transfer between the plasma flow and reactor walls were calculated from all the measured data using the heat balance equations [2].

Results and discussion

At the entrance of the reactor, at the distance up to $x/d \leq 5.6$, the behaviour of plasma flow is different comparing to the distance of $x/d > 5.6$. As the plasma flow enters the reactor through the narrowing tube where the dispersed particles and its carrying air and propane gases are injected, the plasma flow becomes disturbed. Heat transfer in this region could be treated as heat transfer in the entrance region of the circular tube with a sharp inlet. Meanwhile, in the distance $x/d > 5.6$, the fully mixed plasma flow attaches to the walls and the flow becomes steady [3].

Generalized heat transfer results without additional gases and dispersive particles (Fig. 2) confirms that heat transfer in the entrance region (the distance $x/d \leq 5.6$) of the reactor is lower than in the further reactor lengths. The heat transfer in the beginning of the reactor can be described with the following equation:

$$Nu_x = 7 \cdot 10^{-3} \mathrm{Re}_x^{0,92} \left(\frac{T_f}{T_D} \right)^{0,9} . \quad (1)$$

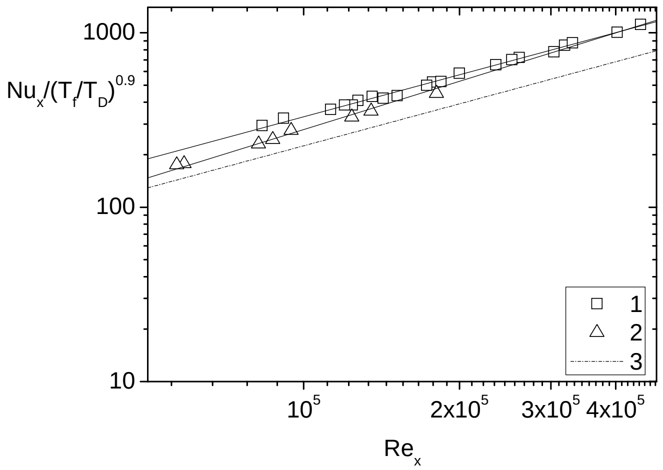


Fig. 2. Generalized heat transfer in the reactor without additional gases. 1 – *x/d*>5; 2 – *x/d*≤5; 3 – classical curve of the heat transfer

The indicator above the Re_x is equal to 0.92. It means that plasma flow is in transition flow region between laminar and turbulent. When the Re_x increases, the Nu_x values are approaching to the steady-state values of the plasma flow, which for the distances *x/d*>5.6 could be described using turbulent flow equations where the indicator above Re_x is equal to 0.8:

$$Nu_x = 33 \cdot 10^{-3} \mathrm{Re}_x^{0,8} \left(\frac{T_f}{T_D} \right)^{0,9} . \quad (2)$$

Classical curve for heat transfer of flows in the circular tubes is written as:

$$Nu_x = 25.5 \cdot 10^{-3} \mathrm{Re}_x^{0,8} \left(\frac{T_f}{T_D} \right)^{0,9} . \quad (3)$$

The values of heat transfer results obtained in this work for the entire reactor length is around 7% higher compared to the classical case. It can be explained with the fact that up to 10% error can be obtained because of very high reactor channel surface roughness [4].

The additional air flow makes the plasma flow turbulent even in the beginning of the reactor. In this case heat transfer in the reactor is described with turbulent flow equations. Generalized equation for distance *x/d*≤5.6:

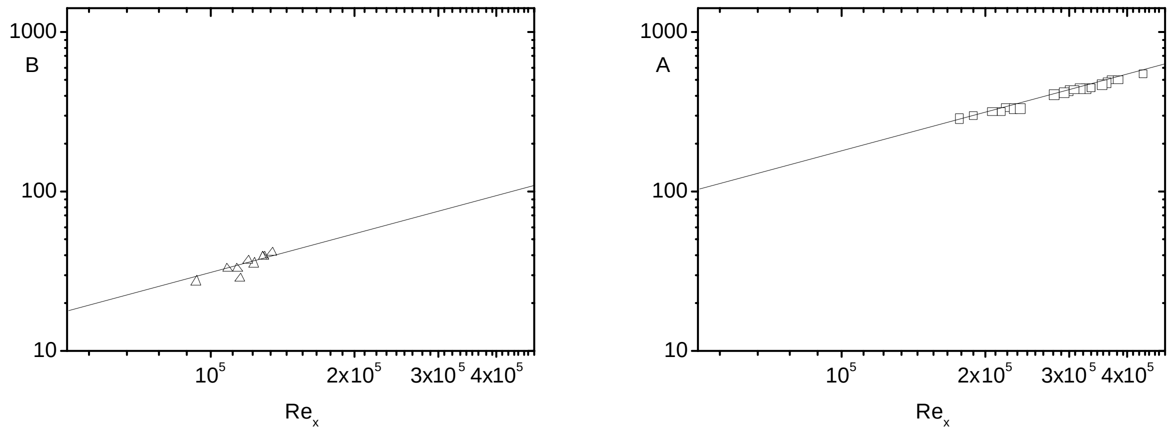
$$Nu_x = 13{,}5 \cdot 10^{-3} \mathrm{Re}_x^{0,8} \left(\frac{G_{1,2}}{G_3} \right)^{0,27} \left(\frac{T_f}{T_D} \right)^{0,9} \quad (4)$$

and *x/d*>5.6

$$Nu_x = 40 \cdot 10^{-3} \mathrm{Re}_x^{0,8} \left(\frac{G_{1,2}}{G_3} \right)^{-0,1} \left(\frac{T_f}{T_D} \right)^{0,9} \quad (5)$$

The factor above the member ($G_{1,2}/G_3$) in equations (4) and (5) which describes the influence of additional air to the heat transfer is bigger in (4) which means that in the reactor distances *x/d*≤5.6 the additional air influence is higher.

The measured heat transfer results with addition of propane gas flow without dispersive particles to the reactor channel shows that the heat transfer to the walls decreases in the whole length of the reactor and especially in the first section, the distance $x/d \leq 5.6$, where the plasma flow becomes turbulent (Fig. 3).



a) b)

Fig. 3. Generalized heat transfer in the reactor with additional gas flows. a – $x/d \leq 5.6$; b – $x/d > 5.6$.

$$A = \frac{Nu_x}{(G_{1,2}/G_3)^{-0,1}(G_g/G_{1,2,3})^{-0,21}(T_f/T_D)^{0,9}}; \quad B = \frac{Nu_x}{(G_{1,2}/G_3)^{0,44}(G_g/G_{1,2,3})^{-0,23}(T_f/T_D)^{0,9}}.$$

The real decrease of heat transfer might be lower, because in our calculations we accept that all propane gas flow burns immediately with sudden plasma flow temperature increase. But propane gas flow doesn't burn immediately. So, the measured heat transfer is possibly too small compared to our calculated flow temperature. In the further distances $x/d > 5.6$, the heat transfer decreases also. It is explained by decrease of oxygen level, which is not sufficient for propane combustion.

Generalized heat transfer for distance $x/d \leq 5.6$:

$$Nu_x = 2,3 \cdot 10^{-3} \operatorname{Re}_x^{0,8} \left(\frac{G_{1,2}}{G_3}\right)^{0,44} \left(\frac{G_d}{G_{1,2,3}}\right)^{-0,23} \left(\frac{T_f}{T_D}\right)^{0,9} \qquad (6)$$

and $x/d > 5.6$

$$Nu_x = 18 \cdot 10^{-3} \operatorname{Re}_x^{0,8} \left(\frac{G_{1,2}}{G_3}\right)^{-0,1} \left(\frac{G_d}{G_{1,2,3}}\right)^{-0,21} \left(\frac{T_f}{T_D}\right)^{0,9} \qquad (7)$$

From the equations (4) and (6) it can be seen that after adding propane gas, the additional air influence on heat transfer increases. That means that propane gas mixes with cold air flow in the beginning of the reactor and do not burn. When the propane burning begins, the additional air influence to heat transfer becomes the same as if there were no propane gas.

The propane gas influence on heat transfer, which is characterized by the member ($G_g/G_{1,2,3}$), is more or less the same in the whole length of the reactor.

The plasma flow temperature, velocity and turbulence can be monitored by adjusting the air and propane gas flow in the reactor which is very important when controlling the plasma flow and dispersed materials interaction.

When dispersive ceramic particles are injected into the plasma flow, part of its energy is used to heat the particles and melt them. In this case the above generalization of heat transfer in plasma flow with dispersive particles could not be used directly. To determine the part of plasma flow energy used for injected material heating and melting special experiments were provided.

The heat transfer drop with addition of dispersive particles was determined by measuring the difference of the heat fluxes to the reactor walls without presence of particles and with them in plasma flow. The ratio between heat flux to the reactor walls and amount of heat maintained by the plasma flow roughly shows how much heat the dispersive particle flow absorbs.

These experiments were performed at three different plasma-chemical reactor regimes, presented in Table 1. The plasma flow parameters were chosen so, that injected particles were heated at temperatures near melting point, but not melted to prevent the formation of the melt layer on the reactor walls. The Al_2O_3 particles 40-60 µm of size were injected into the plasma flow with constant $3.3 \cdot 10^{-3}$ kg/s flow rate.

Table 1

Plasma-chemical reactor regimes

Regime	PT power, kW	Air flow G_1+G_2, g/s	Air flow G_3, g/s	Plasma flow temperature, K
1	53	12	1.5	2900
2	62	12	1.5	3150
3	62	16	1.5	2700

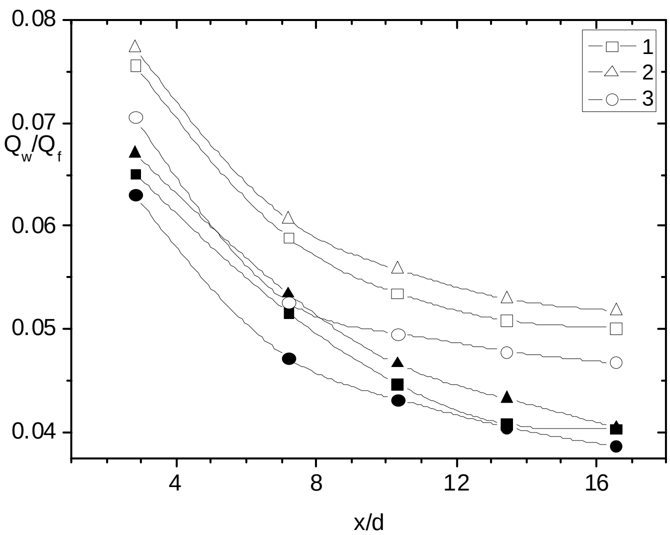


Fig. 4. Axial distribution of relative heat flux intensity of single- and multi-phase flow in dependence on operating regime of the reactor. 1-3 – corresponds the regimes presented in Table 1. Solid and hallow figures represent the work with and without dispersive particle, respectively

As the heat flux to the reactor walls was calculated by measuring the cooling water temperature changes in each individual section, the obtained heat flux decrease values can be considered as an average values in the section length, rather than as a value in a specific reactor relative distance *x/d*, so in Fig. 4 those values are placed in the centre of each section.

In Fig. 4 the ratio between the heat flux to the reactor walls and the quantity of heat maintained by plasma flow (Q_w/Q_f) is shown, when the reactor was working with and without dispersive particle flow. It can be seen that the most intensive heat transfer to the reactor walls is at the entrance region of the reactor, where the plasma flow temperature is the highest.

From these experiments some assumptions about the influence of dispersive particle addition to the reactor channel on the character of plasma flow can be made. Especially it can be seen at distances $x/d>10$ where the plasma flow is in steady-state (Fig.4). When the reactor is working without dispersive particles, the character of ratio Q_w/Q_f is more horizontal than after the dispersive particle addition. As the temperature of dispersive particles entering the reactor is considerably lower than plasma flow, plasma flow energy is used for particle heating and melting. The additional injection of dispersive particles decreases the heat flux to the reactor walls by average of 16 %. So it could be stated, that this amount of energy is used for heating and melting of ceramic particles

Our experiments show that size, shape, composition and flow rate of dispersed particles may have a significant influence on heat transfer to the reactor walls. For the confirmation of such statement, four distinctly different dispersive particle size in ranges of 0.04–0.06, 0.06–0.16, 0.16–0.2 and 0.2–0.25 mm consisting of SiO_2, Al_2O_3, $Al(OH)_3$, and zeolites (chemical composition (mass %): Al_2O_3 − 40.9; SiO_2 − 55.2; Fe_2O_3 − 0.9; TiO_2 − 1.4; CaO − 0.5, MgO − 0.49, Na_2O − 0.2) were studied at the constant plasma flow parameters in all experiments (regime 3 in Table 1). It was observed that the increase of concentration of such particles in the plasma flow has a significant influence on the drop of heat losses to the reactor walls (Fig. 5). When the concentration of dispersed particles in the plasma flow exceeds 0.2 the decrease of the heat flux to the reactor walls is more noticeable.

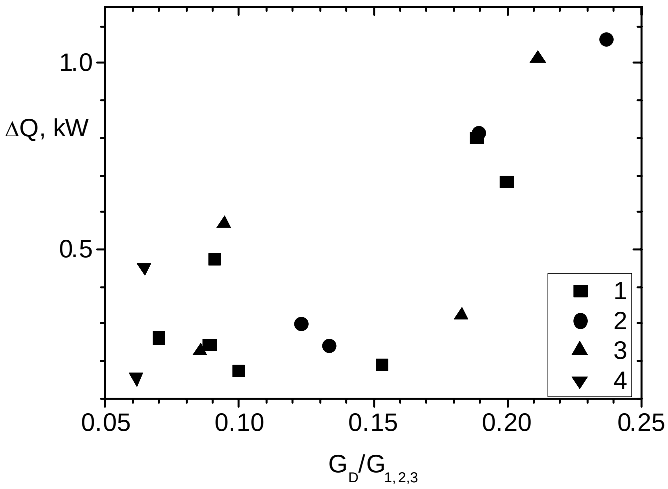


Fig. 5. The influence of dispersed particle diameter on the reduction of heat transfer to the reactor walls during the time unit. 1 – SiO_2, 2 – Al_2O_3, 3 – $Al(OH)_3$, 4 – zeolites

However, it is important to notice, that any patterns of particle size or composition influence on the heat transfer in the reactor could not be made from our results.

Conclusions

1. When the reactor is working without additional gases and dispersive particles, the heat transfer in its entrance region ($x/d \leq 5.6$), is lower than in the further reactor lengths, the distance $x/d > 5.6$. In reactor distances $x/d \leq 5.6$ the plasma flow is in transition flow region between laminar and turbulent, while at $x/d > 5.6$ the plasma flow is turbulent.
2. The additional air and propane gas flows decreases the heat transfer to the reactor walls, and especially in the reactor distance $x/d \leq 5.6$. The plasma flow becomes turbulent in the whole reactor length.
3. The injection of dispersive particles decreases the heat flux to the reactor walls by average of 16 % in the entire reactor length.
4. The increasing mass concentration of dispersive particles in the plasma flow from 0.05 to 0.15 decreases the heat flux to the reactor walls up to 0.5 kW. The further increase from 0.15 to 0.25 is more significant – the heat flux to the reactor walls decreases up to 1.1 kW.

Acknowledgement

This research was partly funded by a grant (No. TAP LB 07/2012) from the Research Council of Lithuania.

Notation

G – air flow rate, g/s, Nu – Nusselt number, Re – Reinolds number, T – temperature, K, Q – heat flux, kW, x – length, m, d – diameter, m.
p – dispersive particles, g – gas, f – flow, D – dissociation, w – wall.

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