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Estimation of Temperature Difference and Integral Flow through Channel of ICF

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Abstract

The transit integral flow trough the channel and resulting temperature difference is extremely important in application of induction channel furnace. Estimations showed that thermo-gravitational force is the leading force that drives the flow through the channel. The transit flow highly depends on geometry of channels, power, heat losses, viscosity and other factors. One of the other factors is growth-up of channels during melting. The grown material is shown to be fractal like which occurs due to diffusion limited accumulation of oxide particles to the surface. Therefore, the growth-up influences the cross-sectional area of the channels and consequently the transit flow and temperature difference in the channel. As particular examples melting of zinc and steel are considered.

Introduction

The efficiency of induction channel furnaces (ICF) significantly depends on transit flow through the channels. The higher the transit flow the more efficient becomes heating of the bath and temperature difference becomes smaller. The first aspect is important for energetic efficiency of the furnace while the second is important for the quality of the final material. As shown in [3] the leading driving force of the flow through the channel comes from thermo-gravitational origin. The electromagnetic force creates intense local movements of the melt, but it has lower influence in integral flow through the channel that thermo-gravitational force. Nevertheless, these local movements created by electromagnetic force are extremely important for effective thermal conductivity and viscous resistance in the channel as well as heat losses from the channel.

Another point is that geometry of channel changes during the exploitation of the furnace due to erosion and deposition of wall material. Therefore, the lifetime of channel furnaces is limited. A typical lifetime of channels in ICF does not exceed a year because of build-up formation on channel walls as well as erosion at certain places. The most dangerous zones of the ICF are placed near the openings of channels. It is the fractal type of build-up formation that intensifies the process and contracts the life-time of channel [1]. From the technological point of view it is especially important to know the conditions under which the character of build-up growth changes from uniform to fractal.

As it was found earlier the growth character of the channels is diffusion limited. Therefore, detailed knowledge about mass transport towards walls during turbulent pipe flow is required. Mass transfer to smooth walls is studied very well. The results of experimental investigations of heat and mass transfer to rough walls for turbulent flow are shown in papers [2] where dependence of Sherwood number on Reynolds number is studied. It was shown that roughness increases overall mass transport to channel walls considerably. The increasing Reynolds number is associated with the disruption of the viscous sublayer and penetration of turbulence into the valley or hole regions, and thus it is associated with increased rate of mass transfer. The described experimental analysis however does not show behaviour of viscous sublayer around particular roughness element. Another difficulty is that according to experimental investigations, the power constants of mass transfer to the rough wall significantly depend whether roughness is regular or irregular 3D structure.

At the same time roughness slightly increases also friction of the flow through the channels which highly influences the effectiveness and lifetime of the ICF. The dependence of average flows through the channels is studied by linear model where main driving force is inhomogenity of temperature along the channels. The roughness plays more important role at high transitional Reynolds numbers when the friction of the flow gets higher. At the same time growth-up of walls increases the liberated heat at that part of the channel. It was shown that roughness of the wall at one channel can even reverse the direction of the flow.

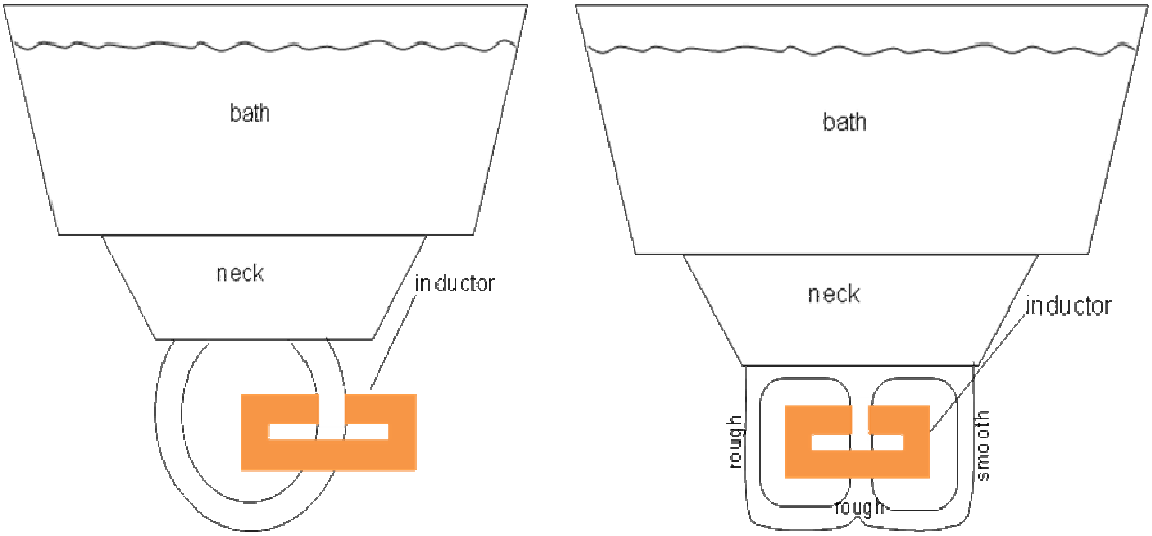


Fig. 1. Scheme of the one-loop (left) and double-loop (right) of ICF

1. Melt Flow in Channels

Because of high electromagnetic forces intense turbulent motion of fluid is present in the channels. However, the electromagnetic force itself is usually not the leading mechanism that creates oriented motion of melt through the channels (see Fig. 1) [3]. Instead the thermo-gravitational force is responsible for oriented motion of fluid. Corresponding Langrangian of transit flow is given by

$$L(s_i, \dot{s}_i, t) = \sum_i \int_{L_i} \left(\frac{\rho(l)}{2} \left(v + \frac{\dot{s}_i}{A} \right)^2 A - \rho \left(l - \frac{s_i}{A} \right) g h(l) A - |s_i| \frac{f_r(l)}{A} \right) dl\,, \tag{1}$$

where i is loop number (first, second and central); s_i is small shift of fluid by respective volume; A – area of channel cross-section; h – coordinate in vertical axis along free gravitational axeleration; f_r – resistive force density; ρ - density; l – distance along the channel. Minimising the functional we obtain the equations of flow dynamics

$$\begin{aligned} \dot{q}_1 \int_{L_1} \frac{\rho(l)}{A(l)}\, dl + (\dot{q}_1 + \dot{q}_2) \int_{L_c} \frac{\rho(l)}{A(l)}\, dl = g \left(\int_{L_1} \frac{d\rho}{dl} h(l) dl + \int_{L_c} \frac{d\rho}{dl} h(l) dl \right) - \\ - \operatorname{sign}(q_1) \oint_{L_1} \frac{f_r(l)}{A(l)}\, dl - \operatorname{sign}(q_1 + q_2) \oint_{L_c} \frac{f_r(l)}{A(l)}\, dl \end{aligned}\,, \tag{2}$$

$$\dot{q}_2 \int_{L_2} \frac{\rho(l)}{A(l)}\,dl + (\dot{q}_1 + \dot{q}_2) \int_{L_c} \frac{\rho(l)}{A(l)}\,dl = g\left(\int_{L_2} \frac{d\rho}{dl}\,h(l)dl + \int_{L_c} \frac{d\rho}{dl}\,h(l)dl \right) - \\ - \operatorname{sign}(q_2) \oint_{L_2} \frac{f_r(l)}{A(l)}\,dl - \operatorname{sign}(q_1 + q_2) \oint_{L_c} \frac{f_r(l)}{A(l)}\,dl \quad . \tag{3}$$

The integral of free turbulent resistance looks

$$\int_{L_i} \frac{f_r(l)}{A(l)}\,dl = 0.11 \int_{L_i} \rho \frac{v_x^2}{2D} \left(\Delta_r + \frac{68}{\mathrm{Re}_D} \right)^{0.25} dl + \sum_e c_e \rho \frac{v_{x_e}^2}{2}, \tag{4}$$

where the second term corresponds to either of turbulent resistance at the entrance or curved part of the channel; $Re_D = \frac{\rho q D}{\eta A}$, where η is dynamic viscosity. Coefficients c_j can be found in tables [4]. The temperature distribution is solved by 1D model where Joule heat and heat losses are accounted. The resulting impedance with respect to purely active resistance R_0 of cylindrical channel at frequency 0 is

$$\frac{Z}{R_0} = \frac{x}{1 - i} \frac{B_{J0}((1 - i)x)}{B_{I1}((1 + i)x)}, \tag{5}$$

where B_{J0} and B_{I1} are Bessel functions and $x = r_0/\delta$. So the Joule heat slightly increases with frequency at given amplitude of current.

In order to see the effect of roughness, let us assume that one loop is smooth (see Fig. 1 right). The typical development of flow in melting of zinc with volume of 2.1 m^3 is given in Fig. 2 left. The final directions of transit flows depends considerably on the initial perturbations (see Fig. 2 right). The first symbol *p*-positive or *n*-negative denotes flow direction in first channel in respect to arrow in Fig. 3 right and the second symbol - in second channel.

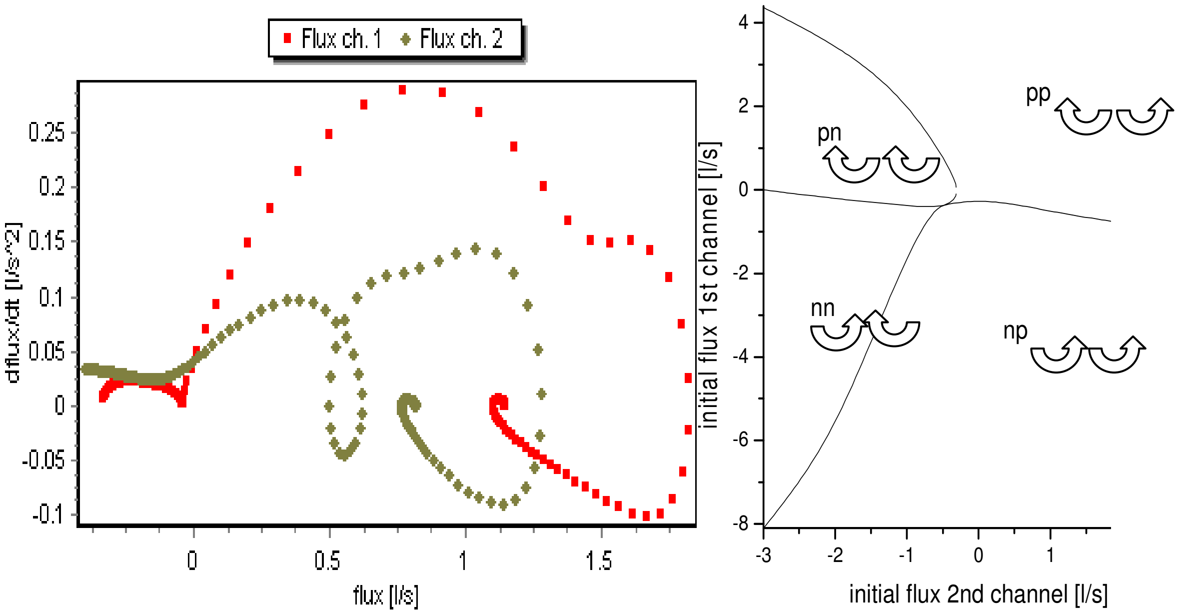


Fig. 2. Left – development of increase of melt flow vs. melt flow itself in melting of zinc in ICF near double critical point in right figure. Right – dependence of flow direction (shown by arrows (see also Fig. 1 right)) in stationary case from initial perturbation

The dependence of fluxes and temperature difference increases according to power law as shown in Fig. 3. Fig. 4 suggests that roughness of channel walls start to influence already at 1 mm. That leads to increase of temperature difference and less proper melting. Fig. 5 shows the dependence on tilt of the furnace in gravitational field. It shows that shift does bring much influence in fluid flow and only at near horizontal tilt there is significant increase in temperature difference and decrease of flow velocity.

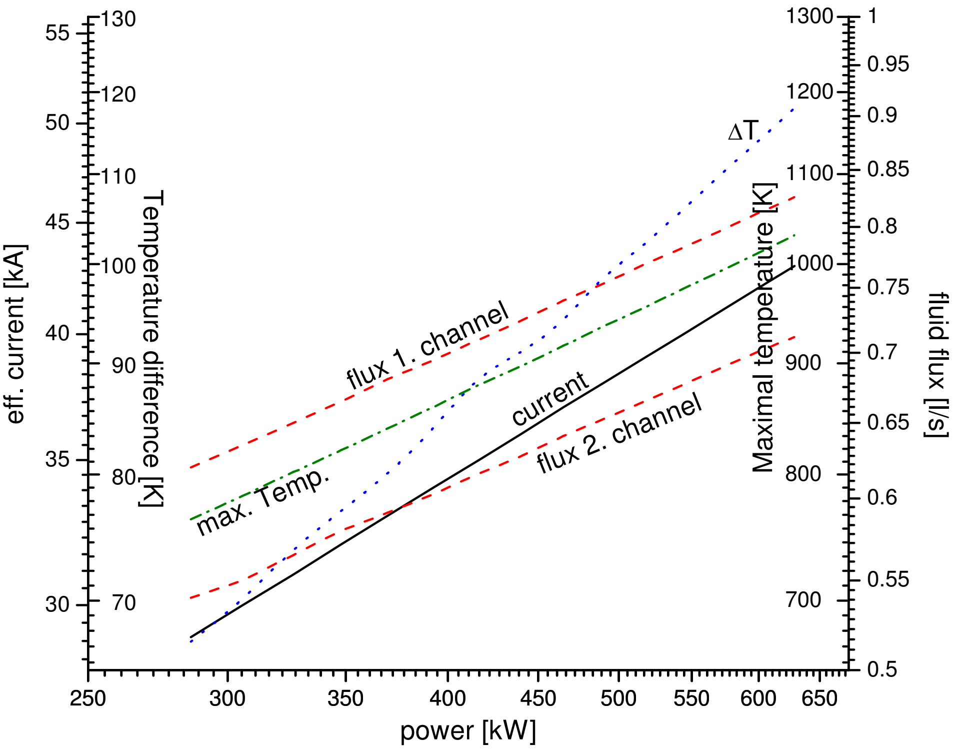
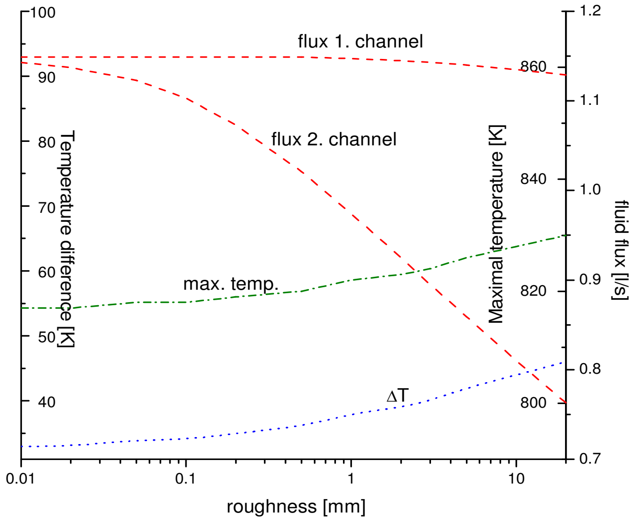


Fig. 3. Dependence of current, fluxes, temperature difference and maximal temperature on power in melting of zinc. One can see that fluxes $q \sim P^{1/3}$, max. $T \sim P^{1/3}$, current $I \sim P^{1/2}$, $\Delta T \sim P^{2/3}$



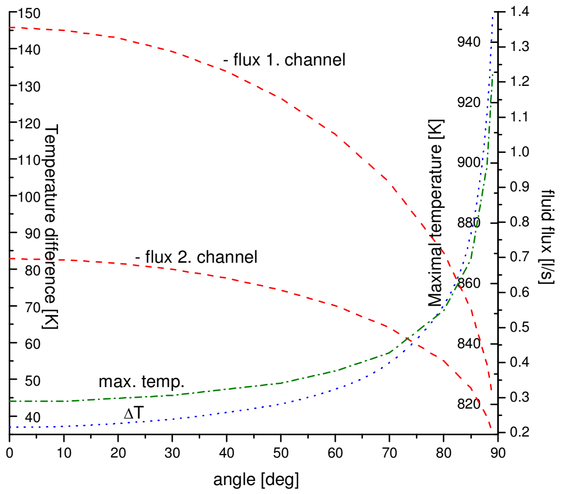


Fig. 4. Dependence of integral parameters on roughness of channel walls in melting of zinc. Flow through the first channel does not change much because its part is set to remain smooth

Fig. 5. Dependence of temperature difference, maximal temperature and fluxes on angle of inclination of the channel. Fluxes are oriented downwards in side channels

2. Growth-up of Channel Walls

The experimental observations show that laminar sub-layer acts as bottle neck for accumulation of oxide to the surface. Fractal like deposition forms if the flux of oxide particles is much higher than flattening of surface due to surface diffusion. The flux of oxide molecules is given by

$$j = \frac{D}{\delta}(c_\infty - c_0), \qquad (6)$$

where D is diffusion coefficient in laminar layer, δ - thickness of laminar layer, c_∞ - concentration of oxide in the bulk of fluid,

$$c_0 \sim \exp\left(-\frac{C}{T}\right) \qquad (7)$$

– equilibrium concentration of oxide near the wall, T- temperature, C – some constant. Thus, the fractal like character and deposition rate increases first if thickness of laminar layer is smaller and second if concentration difference between bulk and equilibrium is higher.

The first one is present at places with higher kinetic turbulent energy that is usually at the exits of channel. That is exactly as experiments have shown. Fractal like deposition suggests that it growth is self intensifying, i.e., if it is already started then it will continue with more speed because of higher diffusive transport to channel walls. This is because fractal like structures reduces the effective thickness laminar layer.

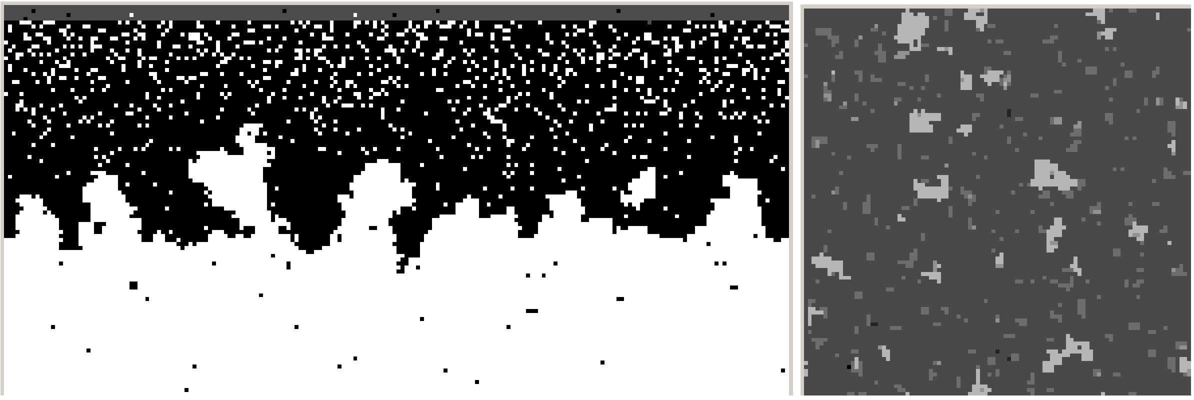


Fig. 6. Monte Carlo calculations of growth of fractal like structure (white - wall and oxide, black –melt). Left – side view to the surface, right – top view to the surface

The second aspect that intensifies the fractal growth and deposition rate is high difference of concentrations between the bulk and the equilibrium concentration at the wall. The concentration of oxides in the bulk increases if the melts get some oxygen atoms either from air or the oxide walls. If the melt is not chemically inert it could hit some oxygen from the wall that will increase the oxide concentration in the bulk and consequently increase the deposition rate. From another side, the concentration difference is higher if equilibrium concentration c_0 is smaller, i.e., temperature is smaller. Therefore, deposition rate will be higher at places with smallest temperature, where turbulent kinetic energy is still significant. One of such places is bottom of the neck between the channels as confirmed by experimental observations.

2D Monte Carlo studies of this diffusion limited growth is shown in Fig. 6. As can be seen fractal like structure could arise depending on concentration of oxide molecules in the bulk, saturated concentration of oxide molecules near the surface, thickness of laminar sub-layer. Moreover, the Fig. 6 show that clusters of surface elements can be washed by intense flow and erosion of the surface is possible, too. The shape of the laminar boundary sub-layer somewhat reproduces the shape of the surface. However, the smaller details of the surface are smoothed and variation of thickness of laminar sub-layer occurs. If the roughness of the surface is small we can use Fourier analysis of the intensity of growth depending on the wave number of roughness of the surface. It suggests that roughness with very large wave numbers i.e. sharp ones decreases during the accumulation because of energetic reasons. At the same time the thickness of laminar sub-layer remains constant for roughness with small wave number i.e. wide ones and speed of growth is limited. The highest speed of growth is for middle wide roughness which is both energetically reasonable and change the thickness of laminar sub-layer. 3D Monte Carlo simulations of surface structure Fig. 6 left shows that fingering of the surface occurs.

Conclusions

- One-dimensional model is constructed for calculation of transit flows and temperature distribution required for study of stability of melting process in ICF.
- Fractal like structure of surface growth-up appears because of diffusion limited accumulation of melt oxide. That is shown by 2D and 3D microscopic Monte-Carlo model.
- The transit flow of melt could be influence if roughness of channel walls is of order of 1 mm in size.
- The smaller is the size of bath and smaller effective thermal conductivity of melt the larger becomes either instability or oscillations of flows during melting.
- The deposition rate increases increasing turbulent energy of the melt, decreasing temperature, increasing roughness of the wall, e.g., by fractal formation, increasing oxide concentration in the melt, e.g., by erosion.

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