A NUMERICAL STUDY OF THE DYNAMICS OF STEEL MELT FLOW IN A TUNDISH

Nicolau A. Branco and Atila P. Silva Freire
Mechanical Engineering Program (PEM/COPPE/UFRJ),
C.P. 68503, 21945-970 - Rio de Janeiro - Brazil.

Abstract. *The dynamics of liquid steel flowing in a tundish is numerically studied for a set of design and operating parameters. The emphazis here is on assessing the effects that the presence of a large concentration of small particles may have on the turbulence properties of the flow. The work uses the modified two-equation differential model developed by Rogers and Eaton(Phys. Fluids A, 3, 928-937, 1991) to describe the turbulence. The work also applies a Lagrangean model to the problem of finding the resindence time distribution of particles in a tundish. Results shown that depending on the particle concentration and on the particle diameter a large degree of attenuation can be found for the turbulent kinetic energy levels.*
Key words: *tundish, continuous steel casting, Kappa-Epsilon model.*

1. INTRODUCTION

The past 40 years have withnessed an impressive increase in the share of steel made by continuosly casting. In fact, it is estimated that more than 90% of the world steel production is currently dependend on this technology. Therefore, it is only natural to expect that great concern is placed on undestanding how the fluid flow in the tundish and in the mold will affect the slab cast quality.

The tundish is an intermediate vessel placed between the laddle and the mold whose purpose is to distribute liquid metal to different moulds of the continuous casting machine. During the time in which the liquid metal remains in the tundish a good opportunity exists for the performance of some metallurgical treatments such as the removal of non-metallic inclusions, alloy trimming of stell and calcium induced inclusion modification. Thus, the geometry of tundishes has been largely studied in literature to understand the role that flow control devices such as dams, weirs, baffles with holes and pour pads may have on the production of clean steel.

To assess the effectiveness of a given tundish design, researchers have used basically two approaches: mathematical modelling based on two-equation differential turbulence models, and water modelling in full or reduced scale models. Of course, all approaches are subjected to their own difficulties. These will be shortly reviewed in the next section.

However, one difficulty that has not yet been addressed in literature is the effect that small particles released in the liquid steel or water flow may have on the final flow configuration, thus misleading any general conclusion we may want to make about the actual liquid steel flow. We know that the removal of inclusions is primarily determined by a balance between the drag forces resulting from the turbulent velocity field and the Stokes forces resulting from buoyancy and that, therefore, the correct evaluation of the velocity field is crucial for the calculation of particle trajectories.

The standard procedure in all works is to completely desconsider the effects that suspended particles may have on the flow configuration. The reasons here are several. In fact, if the particles are fine enough so that their Reynolds number is of order unity, then, it can be shown that the influence exerted by them over the flow pattern is negligible. If, on the other hand, they are present in large enough concentration to have their presence felt by the flow, they may provoke a modification in turbulence properties.

In the former case, the problem of turbulent dispersion of particles is properly analised by Lagrangean methods. In the latter case, when particle concentration is large enough, the momentum loss or gain to the turbulence yielded by the particles can no longer be neglected. Traditional statistical Eulerian approaches must then be altered to incorporate an additional attenuation or amplification of turbulence.

The objective of this work is to assess the effects that the presence of a large concentration of small particles may have on the turbulence properties of a tundish liquid steel flow. This will be made through the theory developed by Rogers and Eaton(1991) and Eaton(1994). These authors modify the momentum equation and the turbulent kinetic energy equation to account for the presence of the particles. The velocity field is then resolved in a formulation having as basis a κ-ϵ turbulence model. The present work also applies a Lagrangean model to the problem finding the resindence time distribution of particles in a tundish.

2. SHORT LITERATURE SURVEY

We start this section with a brief literature survey on articles related exclusively to the mathematical and physical modelling of the flow in a tundish. Then, in the following we will discuss the problem of particles-turbulence interaction. Due to space limitation only a short review of the papers is presented here.

2.1. Mathematical and Physical Modelling of the Flow in a Tundish

The earliest papers resorted to very simple modelling approaches. The paper of Debroy and Sychterz(1985) used an algebraic turbulence model of the mixing length type without a damping function. Of the various tundish configurations studied, the authors concluded that the dam and weir combination provided the best computed cleanliness factor.

The effects that flow control devices such as dams, weirs, slotted dams and submerged gas injection have on the flow properties were subsequently studied by Sahai and Ahuja(1986) in a water model. The work showed that gas injection at a sufficient rate, when coupled with control devices, may reduce the dead volumes by activating stagnant zones; this leads to a homogenization in the vertical cross section across the tundish.

Robertson and Perkins(1986) used a mathematical model for the heat loss mechanisms and the temperature stratification to develop tundish designs which gave optimum temperature distribution over the outlet streams of multistrand tundishes.

He and Sahai(1987) used the κ-ϵ model to solve the three-dimensional averaged Navier-Stokes for a tundish with no dams or weirs but with inclined walls. Prediction of residence time distribution are given which are compared with measurements obtained in water models.

The same κ-ϵ model was used by Ilegbusi and Szekely(1989) to describe the three dimensional velocity field, tracer dispersion, and flotation of inclusion particles, both in the presence and in the absence of an externally applied magnetic field.

The effect of variation of grid spacing on the flow predictions was studied by Chakraborty and Sahai(1991). The main conclusion was that the proper distance of the first computational point from the bottom wall is of primary importance in predicting the RTD curves accurately.

Singh and Koria(1993) studied the flow dynamics in tundishes through a water model for a wide range of design and operating parameters. It was found that the tundish width controls the flow pattern; wider tundishes produced short circuited flow in addition to plug and mixed flow whereas in narrower tundishes no short circuiting is observed.

Joo and Guthrie(1993a, 1993b, 1993c) in a series of three papers proceeded to a comprehensive study of the flow in a tundish. In part one, a sensor equipment was used to the continuous detection of particles suspended in an tundish water flow. In part two, computations were presented to show the importance of thermal natural convection currents in mixing the upper and lower layers of steel. In part three, the attributes of various tundish designs and flow modifiers were studied. The results showed that a conventional biflow, twin-strand, trough-type tundish fitted with flow modifiers allows for the greatest removal of inclusions.

Tanaka et al.(1993) studied the contamination causes of molten steel in the tundish by a continuos metal sampling during operation. The main results were: air oxidation of molten steel is the biggest factor of contamination, the influence of air oxidation decreases and the pollution of slags increases during continuous operation.

Shen et al.(1994) performed velocity and turbulence measurements in a tundish through the laser Doppler velocimetry technique. Laser sheet and powder visualization were also used to provide qualitative understanding of the complex tree-dimensional flow.

Ilegbushi(1994) developed a two-fluid model of turbulence to the flow in a tundish. Transport equations were solved for the variables of each fluid, and empirical relations were used to express the interchange of mass and momentum at the interface.

The composition distribution that develops in a continuously cast steel during a grade change change was studied by Huang and Thomas(1996). The developed model was fully transient and consisted of three submodels for the tundish, the liquid core of the strand and the solidification region. The mixing in the tundish was modelled by two plug flow zones, two back-mixing boxes and two dead volumes.

Barreto-Sandoval et al.(1996) studied the heat transfer in tundishes heated by plasma. The thermal response of the cooling-heating cycles was modelled by a double dispersion coefficient.

Chen and Pehlke(1996) performed a mathematical modelling of tundish operation and flow control to reduce transition slabs. The general dimensional criteria for water modelling of melt flow and inclusion removal in tundishes were investigated by Sahai and Emi(1996). The conclusion was that both Froude and Reynolds number similarity are unimportant; only turbulent Reynolds number similarity is important. For nonisothermal flows, Damle and Sahai(1996) showed that the tundish Richardson number is the dimensionless group that has to be satisfied.

2.2. Particles-turbulence interaction

The interaction between solid particles and the turbulence of the carrier fluid was considered by several authors. Hetsroni(1989) in an very important paper concluded that, in general, the particles with a low Reynolds number tend to suppress the turbulence of the carrier fluid. Particles with Reynolds number larger than about 400, on the other hand, tendo to enhance turbulence.

Rogers and Eaton(1991) studied the response of a turbulent boundary layer in air to the presence of particles. The measurements were made using a single component, forward scatter laser Doppler anemometer. The data clearly demonstrated that the particles damped turbulence, apparently affecting all scales equally. One of these authors, Eaton(1994) showed in a subsequent work through experiments and direct simulation the importance of preferencial concentration in which particles are collected in highly strained regions of the flow.

Other important references on the subject were noted by the present autrors, however, the present limitation is space has prevented us from quoting them here.

3. Theory

The motion equations of continuity and momentum balance for a Newtonian fluid can be written as

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0. \tag{1}$$

$$\frac{\partial (u_i u_j)}{\partial x_i} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu_{eff}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + \rho g_i. \tag{2}$$

where notation here is classical. Thus, $\mu_{eff} = \mu + \mu_t$.

The turbulence is modelled through a two-equation differential model, the model of Jones and launder(1972). The turbulence features are specified by transport equations for the turbulent kinetic energy, K, and its rate of dissipation, ϵ.

The turbulent viscosiy μ_t is given by

$$\mu_t = \frac{C_D\, \rho\, K^2}{\dot{\epsilon}}. \tag{3}$$

The transport equations for K and ϵ are

$$\frac{\partial}{\partial x_i}\left(\rho\, u_i\, K - \frac{\mu_{eff}}{\sigma_K}\frac{\partial K}{\partial x_i}\right) = P_K - \rho\epsilon, \tag{4}$$

$$\frac{\partial}{\partial x_i}\left(\rho\, u_i\, \epsilon - \frac{\mu_{eff}}{\sigma_\epsilon}\frac{\partial \epsilon}{\partial x_i}\right) = \frac{C_1\, \epsilon\, P_K - C_2\, \rho\, \epsilon^2}{K}, \tag{5}$$

where the production term is given by

$$P_K = \mu_t \frac{\partial u_j}{\partial x_i} \left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} \right), \tag{6}$$

These equations were solved considering that at the walls the boundary conditions for the momentum transport processes can be modelled by wall functions. For the transversal velocity component at a wall, zero flux was considered. For the longitudinal component, the no slip condition was used. At the symmetry planes and at free surfaces, the transversal velocity and gradients of all other variables were set equal to zero.

The values of the constants in the κ-ϵ model taken on their standard values; thus, C_1=1.42, C_2=1.92, C_D=0.09, σ_K and $\sigma_\epsilon = 1.30$.

Next, we describe the discrete particle approach that was used here. This method follows each individual particle using the velocity field furnished by the Eulerian approach to evaluate the drag force.

The governing equations for each particle are

$$\dot{x} = u(x) \tag{7}$$

$$\ddot{x} = \frac{F_x}{m} = -\frac{D_x}{m} = -\frac{3\pi\, \mu\, D_p\, (u(x) - u(0))}{m} \tag{8}$$

$$\dot{y} = v(y) \tag{9}$$

$$\ddot{y} = \frac{F_y}{m} = \frac{E_y - P_y - D_y}{m} = \frac{\frac{\pi}{6}\, D_p^3\, (\rho_f - \rho_p)\, g - 3\pi\, \mu\, D_p\, (v(y) - v(0))}{m}. \tag{10}$$

where D_x, D_y denote the drag force, E the buoyancy, P the weight, D_p the particle diameter, m the mass, ρ_f the fluid density and ρ_p the particle density.

The above equations are effectively solved on a different grid from the liquid steel equations so that interpolation is continuously used. Care was taken to avoid numerical errors that could be created by a low order interpolation scheme.

The previous approach had the difficulty of not considering any interaction between the carrier fluid, water, and the particles. Some authors, however, have strongly indicated in the past (Hetsroni(1989)) that particles with a small Reynolds number cause supression of turbulence, whereas particles with higher Reynolds number cause enhancement of turbulence due to wake shedding.

To incorporate turbulence attenuation in the standar Navier-Stokes equations, Rogers and Eaton(1991) suggested that they may be re-written as

$$\frac{\partial \overline{U}_i}{\partial t} + \overline{U}_j \frac{\partial \overline{U}_i}{\partial x_j} = \frac{1}{\rho_f} \frac{\partial \overline{p}}{\partial x_i} + \nu_f \frac{\partial^2 \overline{U}_i}{\partial x_j^2} - \frac{1}{\rho_f} F_i, \tag{11}$$

$$F_i = \frac{\Phi}{\tau_p}\, (u_i - v_i), \tag{12}$$

where F_i is the instantaneous drag force per unit volume applied by the particles to the fluid. The particles are normally considered to occupy a negligible volume fraction so that the continuity equation remains unchanged. Φ is the local particle concentration (mass of particles per unit volume) and τ_p is the particle time constant.

The particles/turbulence interaction appears in as an additional term in the turbulent kinetic energy, which must then be specialized to

$$\begin{aligned}\frac{D}{Dt}K &= P_K - \epsilon - \frac{1}{\rho_f \tau_p}\Big[\overline{\Phi}(\overline{u_i u_i} - \overline{u_i v_i}) + \\ &+ (\overline{U_i} - \overline{V_i})\overline{\Phi' u_i} \\ &+ (\overline{\Phi' u_i u_i} - \overline{\Phi' u_i v_i})\Big]\end{aligned} \tag{13}$$

The production term and the viscous dissipation term are identical to their equivalent in a single phase flow. This equation can be further simplified on order of magnitude grounds. It follows that (Roger and Eaton(1991))

$$\frac{D}{Dt}K = P_K - \epsilon - \frac{1}{\rho_f \tau_p}\Big[\overline{\Phi}(\overline{u_i u_i} - \overline{u_i v_i})\Big]. \tag{14}$$

Equation 14 is identical to the single fase equation with the addition of the last term due to particle drag. The form of ϵ is identical to the equivalent term in the single phase equation. However, the equation for ϵ will be affected by the particles since it is a function of the turbulence.

4. Results

In this section, we will illustrate the differences between results obtained with the standard Eulerian method defined by equations 1 to 5 and the modified equations 11 to 14. This will be made through the tundish geometry shown in Figure 1 and in Table 1. This geometry was based on that described in Nieckele et al.(1992) and will serve as a reference case to the present simulations. The residence time distribution of the particles was evaluated through the Lagrangean approach. The residence time is defined as the time a single fluid element spends in the tundish.

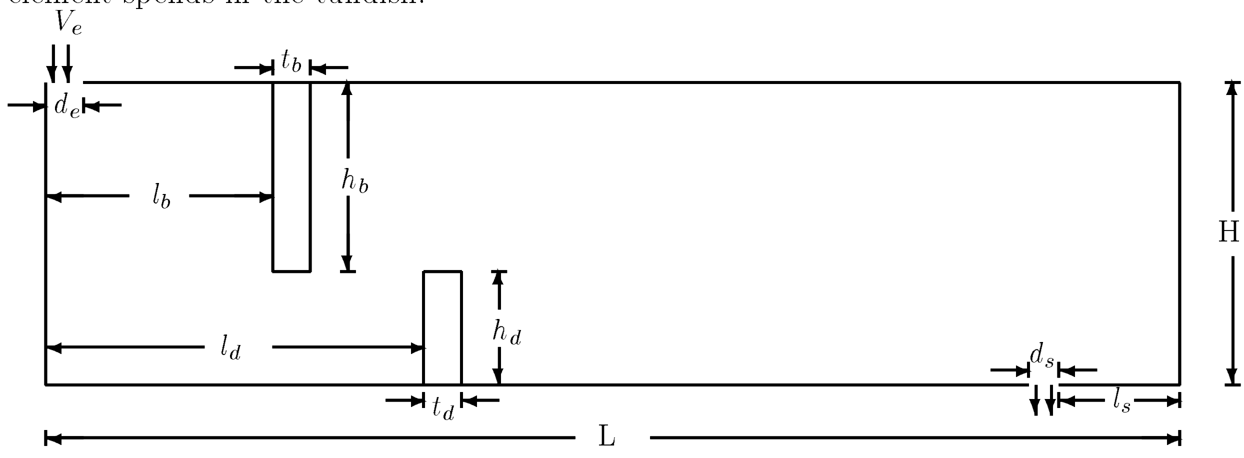

Figure 1: Tundish geometry.

Table 1: Tundish geometry.

Geometry	**Parameter**	**Dimension**	**Unity**
depth	$H = 0,75$	0,75	m
length	$2L = 9,05H$	3,395	m
inlet diameter	$d_e = 0,072H$	0,054	m
oulet diameter	$d_s = 0,072H$	0,054	m
outlet distance from inlet	$l_s = 0,703H$	0,5	m
dam distance from inlet e	$l_b = 0,893H$	0,67	m
dam height	$h_b = 0,693H$	0,5	m
dam width	$t_b = 0,133H$	0,1	m
weir distance from inlet	$l_d = 1,37H$	1,0	m
weir height	$h_d = 0,333H$	0,25	m
weir width	$t_d = 0,133H$	0,1	m
Properties of steel			
density	ρ	7000,0	Kg/m^3
viscosity	μ	6,642E-03	Kg/(ms)

In all simulations we have considered the following particle properties: species, Al_2O_3 and/or SiO_2; mean density, 3000 Kg/m^3; diameter, 20 μm $\leq D_p \leq$ 160 μm. This choice was based on the data given by Joo and Guthrie(1993a).

The calculations for the velocity field were made using as platform the semi-implicit method for pressure linked equations (SIMPLE). The initial conditions were specified as $U_e = 0\ m/s$, $V_e = 0.5\ m/s$, $k_e = 0.01V_e^2 = 0.0025\ m^2/s^2$, $\epsilon_e = \kappa_e^{\frac{3}{2}}/(d_e/2) = 0.0046\ m^2/s^3$.

The numerical calculations show that two large recirculation zones occur in the tundish. These regions work as large dead fluid regions that tend to minimize the spread of residence time and to maximize the average residence time of fluid flowing through a tundish.

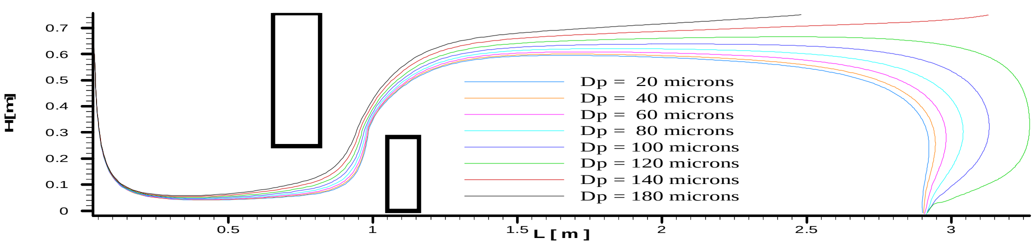

Figure 2: Particle trajectory.

The trajectory of the particles is shown in Figure 2. The resulting residence times are shown in Table 2.

The effects of varying the particle parameters on turbulence attenuation are shown in Figures 3 to 8. These figures were prepared as Φ was made to vary from 0.5 to 6.1 and D_p from 20 μm to 110 μm. The fluid/particle velocity correlation, $\overline{u_i v_i}$ was estimated by Rogers and Eaton(1991) to be of the order of 20 to 50% of $\overline{u_i u_i}$. The constant of time τ_p

Table 2: Particle behaviour in the tundish.

D_p	iter	i_0	j_0	x_f	y_f	t_{res}[s]
—	400	2	21	2.901	-.004	40.000
20 μm	401	2	21	2.902	-.008	40.100
40 μm	405	2	21	2.905	-.009	40.500
60 μm	415	2	21	2.909	-.012	41.500
80 μm	438	2	21	2.914	-.019	43.800
100 μm	489	2	21	2.917	-.003	48.900
120 μm	627	2	21	2.917	-.008	62.700
140 μm	353	2	21	3.129	.750	35.300
160 μm	245	2	21	2.481	.751	24.500
						$\bar{t}_{res} = 42.163$

was determined by the equation $\tau_p = \rho_p D_p^2/18\mu_f$. For the cases above the value used for the fluid/particle velocity correlation was 0.3 (Rogers and Eaton(1991)).

The change in turbulence levels in the large velocity gradient regions is noticeable showing that the currently used mass loads may result in a significant suppresion of turbulence.

5. CONCLUSION

We have shown in the present work how particle presence in a fluid system may alter the properties of turbulence. The work has, in fact, striven to show how a simple theory may be advanced to model a problem which may have an important role in determining the turbulence properties in a liquid steel or water flow in a tundish. The general conclusion was that, depending on the considered particle concentration and particle diameter, the levels of turbulence kinetic energy may be greatly altered.

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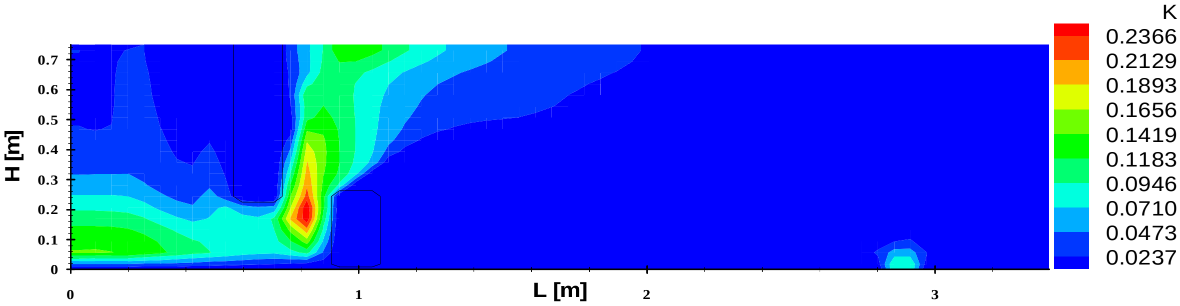

Figure 3: Turbulent kinetic energy, $\Phi = 0$.

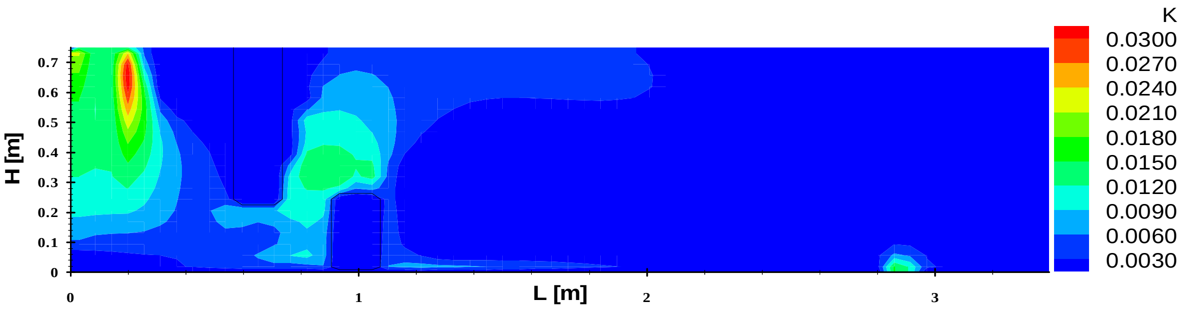

Figure 4: Turbulent kinetic energy, $D_p = 20\mu m$ e $\Phi = 0,5$.

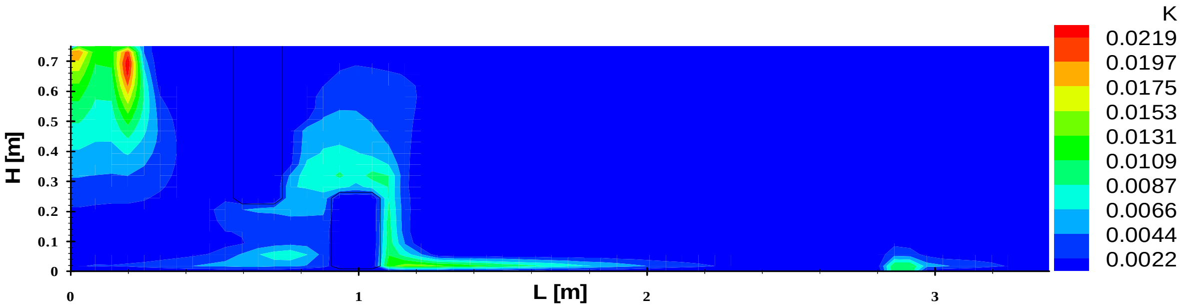

Figure 5: Turbulent kinetic energy, $D_p = 20\mu m$ e $\Phi = 1,0$.

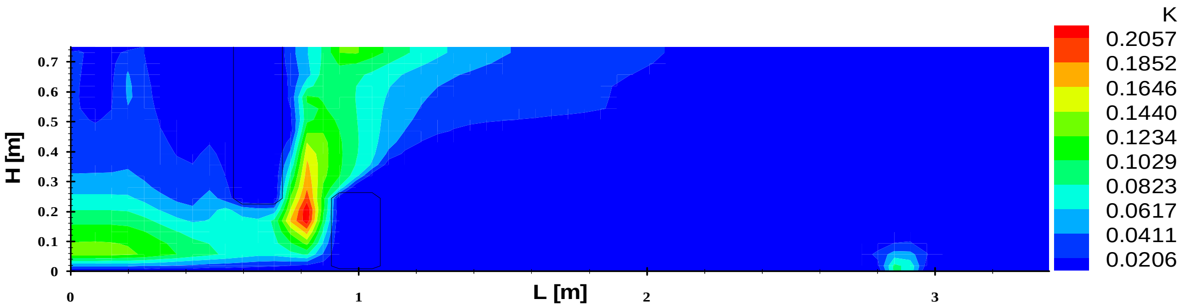

Figure 6: Turbulent kinetic energy, $D_p = 110\mu m$ e $\Phi = 0,5$.

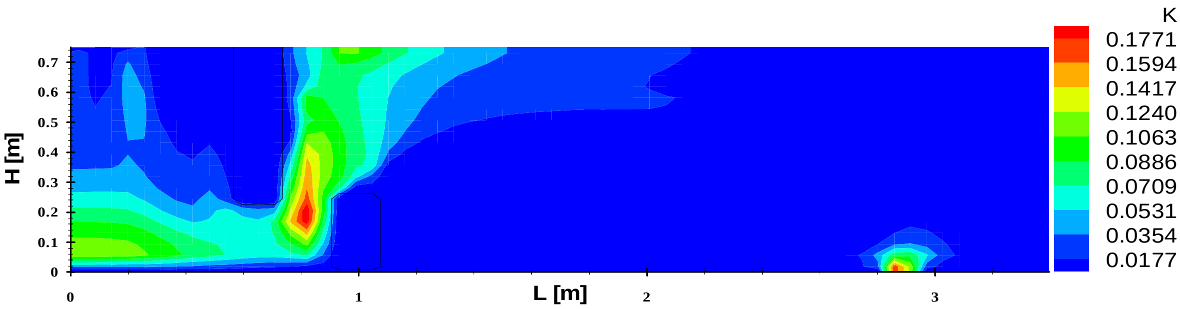

Figure 7: Turbulent kinetic energy, $D_p = 110\mu m$ e $\Phi = 1,0$.

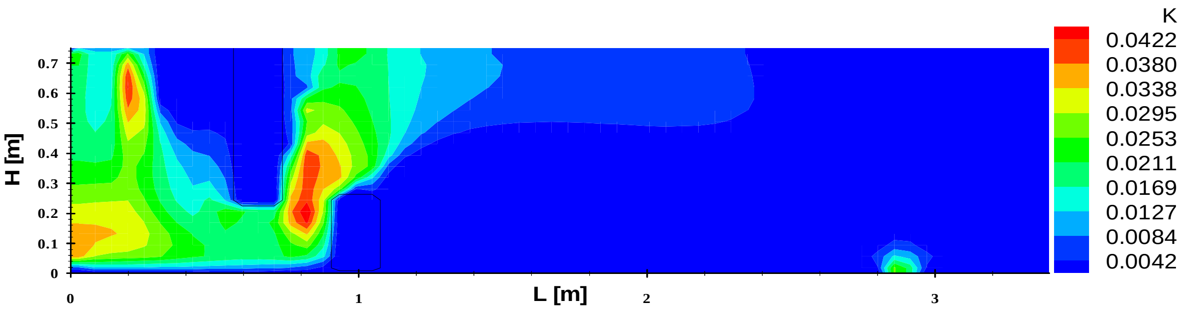

Figure 8: Turbulent kinetic energy, $D_p = 110\mu m$ e $\Phi = 6,1$.