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Heat Transfer and Solidification of Molten Iron in a Pipe

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Authors' contributions

This work was carried out in collaboration between all authors. Author MAB designed the study and wrote the first draft of the manuscript. Author CL performed the computer simulations and author DYM managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

The effect of the pipe wall temperature on the heat transfer and the internal solidification phenomena during the pouring of pure molten iron in a pipe is studied in this work. A mathematical model consisting in the motion, mass balance and heat equations is proposed. The Reynolds Stress Model is employed to simulate turbulence. The mathematical model considering transient three-dimensional simulations is numerically solved using the Computational Fluid Dynamics technique. To simplify the mushy zone problem, pure iron considered. Numerical simulations show that a pipe wall temperature of 300 K promotes early solidification and blockage, and yields strong internal gradients of velocity and temperature. Besides, a pipe wall temperature of 1000 K prevents solidification and promotes a more homogeneous flow and temperatures contours of molten iron in the pipe.

Keywords: CFD; heat transfer; metal solidification; molten iron; pipe blockage.

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1. INTRODUCTION

Given the importance that pipe blockage by internal solidification has nowadays in many industries, this problem has been the subject of research work since several decades ago. Currently, in many iron foundries and steelmaking shops the blockage of runners by solidification of molten metal remains as a very important drawback given that it causes significant economic losses and productivity decrease. In spite of its industrial and academic importance, many aspects of the pipe blockage problem remain unclear and further analytical and numerical research should be done in order to clarify the influence of the main variables in the physics of this problem. A seminal work about the solidification in pipes is reported in [1]. These authors consider a horizontal pipe in which a liquid with constant properties is entering with a laminar flow regime. The pipe walls are kept at a constant temperature, which is below the solidification temperature of the liquid. Steady state is considered, and free convection and axial momentum and heat transfer are neglected. A two-dimensional mathematical model based on mass, momentum and energy balances is proposed and an analytical solution is presented. A strong discrepancy between model results and experimental results when natural convection is taken into account is reported. Pipe blocking is not considered.

An analytical treatment for the transient solidification problem of a liquid flowing through a horizontal pipe with a slug flow is presented in [2]. The energy equation for the liquid and solid phases is considered in the mathematical model, and the solution is based on Henkel and Laplace transforms. Analytical results for the position of the solid-liquid interface agree well with experimental and numerical results exclusively for the steady state condition for small rates of change of the frozen layer. In [3] a mathematical model which considers natural convection is presented; the minimum pressure drop required to prevent the pipe blockage is determined. A numerical analysis of the transient solidification and blockage in tubes under laminar regime is reported in [4], and the inlet mass flow rate is forced to depend on the pressure inlet. Results are presented for a pipe with a length-to-radius quotient greater than ten in order that the radial velocity becomes negligible. Blockage of the pipe depends on the pressure inlet and on the inlet temperature. In [5] the problem of transient solidification and blockage of a molten pure metal in a cold runner is numerically tackled. The flow is considered turbulent, therefore the melt is well mixed and the radial temperature gradients in the molten metal are assumed negligible. This work takes into account the progressive decreasing of the output mass flow rate of molten metal due to the growth of the solidified crust. The continuity and energy equations for both the liquid and solid phases are numerically solved by means of the finite-differences method. The authors analyze the influence of the diameter and length of the runner and the inlet and wall temperatures on the crust solidification rate and runner blockage. They report that the runner diameter is the most critical variable for runner blockage.

The transient solidification of a laminar molten metal in which the pipe walls are externally cooled by convection is investigated in [6]. The authors divide the problem in two parts: a cooling zone of the pipe where the molten metal is solely cooled, and a solidification zone in which the cold metal becomes solidified. The mathematical model consists of the energy equation for both the liquid and solid phases and the coupling condition at the solid-liquid interface. The model is analytically solved through the finite integral and Laplace transforms. The results for the liquid temperature in the first zone and the solid-liquid interface in the second one along the tube length are presented in terms of the Biot and Stefan numbers. In [7] a criterion to predict whether certain system under laminar flow will present blockage is presented. A comparison is made with previous experimental results for solidification of

water, and good agreement is exhibited. In another paper [8], the solidification under turbulent flow is analyzed, and predictions of blockage time are presented for systems with Re numbers between 2 000 and 10 000 and Pr numbers between 0.007 and 0.1. In [9] is reported that pipe blockage occurs when the pressure drop is below a certain critical value, and that blockage is more feasible in a longer pipe at a lower wall temperature.

A work from a dynamical point of view is reported in [10]. Oscillations in the flow rate, the pressure drop and the solidified layer thickness for certain values of the inlet Re number and the coolant temperature are reported. In accordance to this work, if the inlet Re number is increased, the coolant temperature required to start the oscillatory behavior is also increased. Transients which do not yield blockage are analytically studied in [11]. The theoretical results of this work are compared with experimental ones and good agreement is reported for small solidified layer thickness. For large solidified layer thickness and for non-constant wall temperature, significant disagreement is found. In [12] is numerically investigated the effect of natural convection on the solidification of a laminar fluid with large Pr number. It is reported that the growth of the solidified layer is strongly influenced by the superheat, the Rayleigh number and the axial position. The internal solidification of molten metal flows has been mathematically modeled for both steady and transient cases in [13]. The model predicts the solidified layer thickness and the metal flow rate, and an experimental verification of the mathematical model is reported using molten tin. In [14] is addressed the transient solidification of a laminar molten metal inside a convergent nozzle. The flow inside the nozzle is assumed gravity-driven. The energy equation is applied for the liquid region at quasi-steady state and is solved using the separation of variables method.

Some works on iron and steel solidification have been recently published [15-17]. However, it is clear that more studies on the heat transfer and solidification phenomena in pouring pipes are required. In this work the above phenomena is analyzed by numerically solving a mathematical model which consists in the transient three-dimensional version of the mass, momentum and energy equations. Numerical solution is obtained by means of the Fluent Computational Fluid Dynamics (CFD) software, and the critical variable considered is the pipe wall temperature. The Reynolds Stress Model (RSM) is employed to simulate turbulence, and in order to avoid the complexity of the mushy zone, the pouring of pure iron is considered.

2. MATHEMATICAL MODEL

2.1 Momentum Transfer and Mass Balance

The internal solidification in pipes is a complex problem given that in this process coexists fluid flow, mass transfer, heat transfer and phase change. The equations which model the momentum transfer of an incompressible fluid are known as equations of motion, and they are expressed in this way [18]:

$$\rho \frac{Dv}{Dt} = -\nabla p + \mu \nabla^2 v + \rho g \quad (1)$$

Where ρ is the molten metal density, t is time, v is the velocity vector, p is the pressure, μ is the molten metal viscosity and g is the gravity force vector.

Commonly, industrial flows are turbulent in nature. In order to model turbulence properly, the Reynolds Stress Model (RSM) is employed. Currently it is well recognized that RSM simulate turbulence in a better way than two-equations models such as the $k-\varepsilon$ model [19]. RSM is derived from the motion equations and the Reynolds stress tensor [20]. The formulation of the RSM can be found elsewhere [21]. The mass balance is represented by the continuity equation $\partial v_j / \partial x_j = 0$, where v_j and x_j are the j^{th} components of the velocity vector and the coordinate system, respectively.

2.2 Heat Transfer and Solidification

For heat transfer and solidification the following version of the energy equation is employed [22]:

$$\frac{\partial(\rho H)}{\partial t} + \nabla \cdot (\rho v H) = \nabla \cdot (k \nabla T) + S \quad (2)$$

Where H is the molten metal enthalpy, k is the molten metal thermal conductivity, and S is a source term, in this case the latent heat of solidification.

2.3 Initial and Boundary Conditions

The initial conditions are as follows: molten metal inside the pipe is at rest and at the pouring temperature. The boundary conditions are: for velocity, non-slip condition at the pipe wall. The inlet velocity v_y is that corresponding to the mass flow rate M :

$$v_y = -\frac{4M}{\pi D^2 \rho} \quad (3)$$

Where D is the pipe internal diameter. Besides, the thermal boundary conditions are as follows: the inlet temperature is the pouring temperature. At the pipe wall, a constant temperature is assumed.

3. NUMERICAL SOLUTION

The above mathematical model was numerically solved by means of the Fluent CFD software. 3D transient simulations were carried out using a time step of 1×10^{-4} s and the Pressure Implicit Splitting Operation (PISO) algorithm was employed for the pressure-velocity coupling [22]. Pure iron, whose properties are taken from [5], was considered as the molten metal in order to avoid the mathematical complexity of the mushy zone. A pipe with 0.05m of internal diameter and 0.15m high was assumed, see Fig. 1. The pipe wall temperature was considered as the critical variable for heat transfer and solidification. Two pipe wall temperatures were considered, namely 300 and 1000K. The pouring temperature was kept constant at 1860K, and the inlet velocity was fixed at 5m/s.

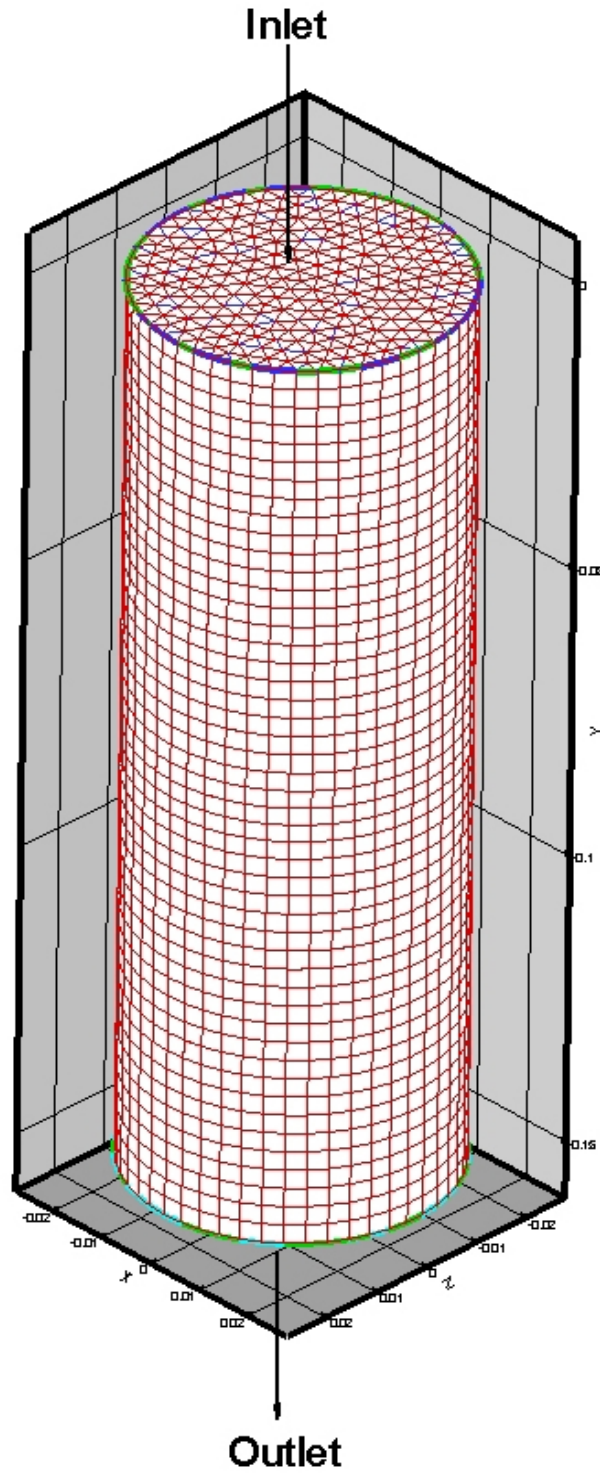


Fig. 1. The pipe

4. MESH-INDEPENDENCE ANALYSIS

A mesh-independence analysis was carried out to show that the numerical results are not dependent on the size of mesh used. Several meshes with different number of cells were tested in order to achieve consistent results. Fig. 2 depicts the temperature contours at the central vertical plane for four cell volumes of 122.7, 50.8, 28.1 and 14.7mm³, corresponding to 2 400, 5 800, 10 000 and 24 000 cells, respectively. It is observed that the temperature contours become similar as the cell volume decreases. The computer simulations showed that beyond 56 000 cells no significant changes in the numerical results are exhibited by the system variables, so this number of cells was employed in the subsequent numerical runs.

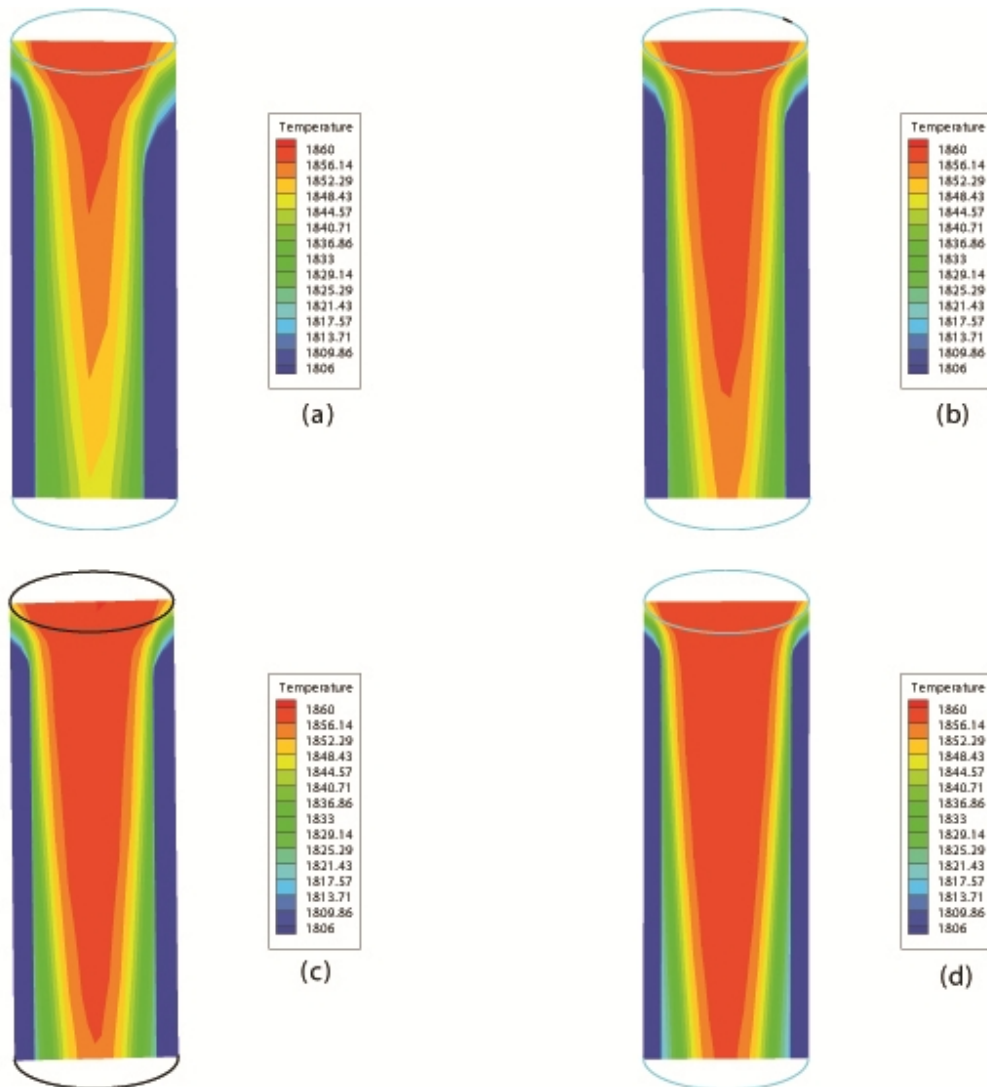


Fig. 2. Mesh convergence test. Contours of temperature (K) after 1 s of elapsed time for a pipe wall temperature of 300K. (a) 122.7, (b) 50.8, (c) 28.1, (d) 14.7mm³/cell

5. NUMERICAL PROCEDURE VALIDATION

Validation is defined as the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model [23]. The process for validation assessment of a CFD simulation encompasses, among other factors, mesh-independence, temporal convergence and comparison of CFD results to experimental data [23]. Mesh-independence was considered in Section 4. Temporal convergence was obtained by considering a time step of 1×10^{-4} s, which yielded residuals under 0.01. However, a direct comparison of CFD results to experimental or published ones was not possible given that no data were available.

6. RESULTS OF SIMULATIONS

6.1 Pipe wall Temperature of 300K

Fig. 3 shows the temperature contours in the central vertical plane after 1 s of elapsed time from the start of pouring. It is observed a significant temperature gradient inside the pipe. In the blue zone, temperature is below the solidification temperature (1806K), therefore this region contains just solidified metal. At the end of the pipe, i.e. a height of 0.15m, the solidified layer is approximately 0.007m thick. Fig. 4 shows a cross view of the temperature distribution at the pipe exit after 5s of elapsed time. As in Fig. 3, blue zone contains the solidified metal. Approximately 60 percent of the initial flow area remains free for flow, whereas the rest is blocked by the solidified metal. In this case a significant blockage is exhibited by the pipe.

In Figs. 5 and 6 are depicted some contours of the vertical component of velocity after 5 s from the start of pouring. Fig. 6 shows that molten metal is accelerated at the center of the pipe exit due to the imposed boundary condition which maintains constant the mass flow rate inside the pipe. For long time runs this boundary conditions is rather unrealistic given that for low pipe wall temperatures the pipe exit can be fully blocked.

6.2 Pipe Wall Temperature of 1000K

Figs. 7 and 8 show the contours of temperature after 5 and 10s, respectively, from the start of pouring for a pipe wall temperature of 1000K. Both figures are similar. For the elapsed times considered, no significant zones with temperature below the iron solidification temperature are observed. This means that no internal solidification is present, at least during the first 10s of elapsed time. In Fig. 9 is depicted the vertical component of velocity after 5s for 1000°K of pipe wall temperature. A very homogeneous radial distribution of temperature and vertical velocity is appreciated for this pipe wall temperature. Given that in this case internal solidification is negligible, no significant drops in velocity are present for the considered pipe wall temperature.

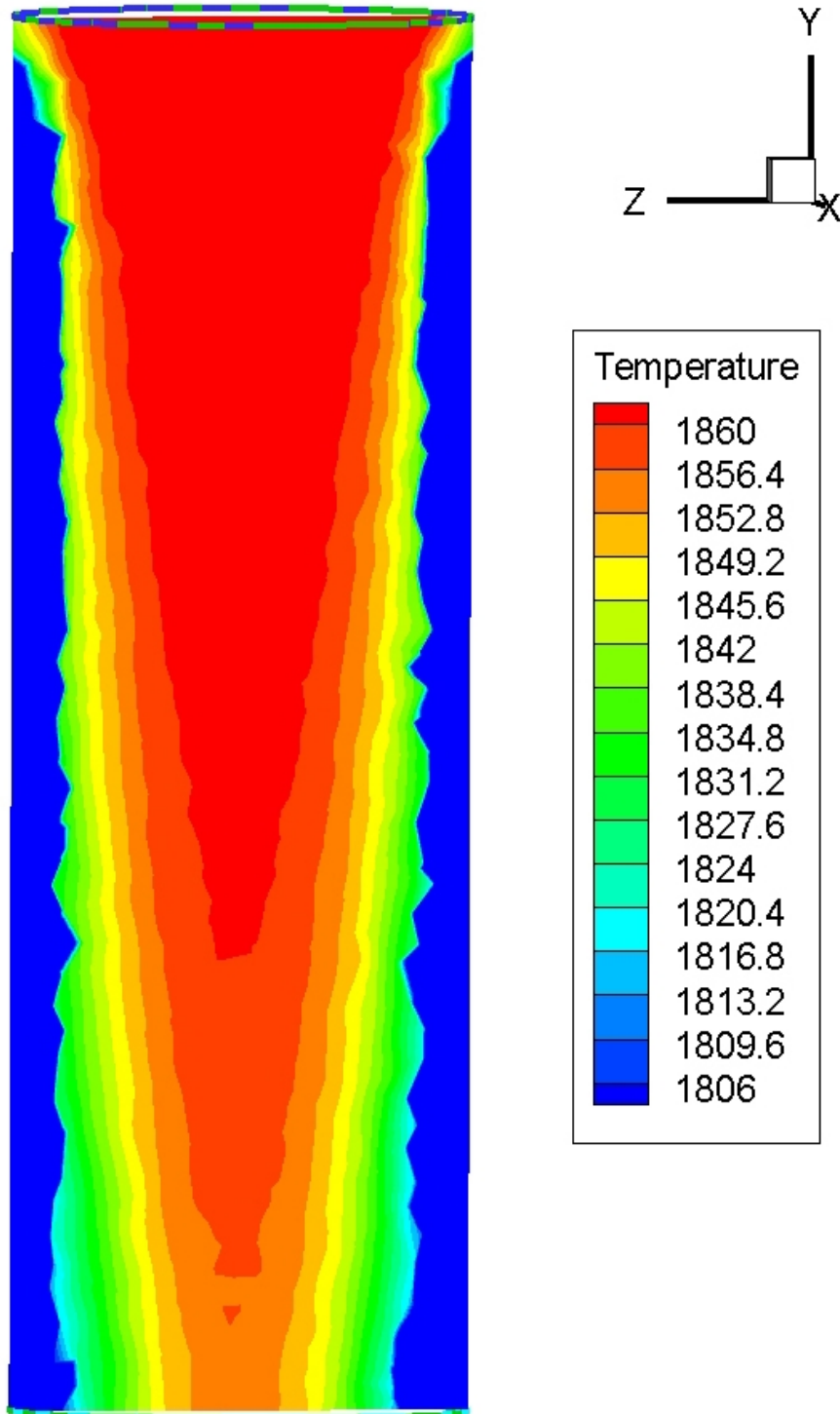


Fig. 3. Contours of temperature (K) after 1s of elapsed time for a pipe wall temperature of 300K

6.3 Remarks

In accordance to Fig. 4, a pipe wall temperature of 300K causes a fast and significant solidification of molten iron for a pouring temperature of 1860K; as result, a significant blockage is exhibited for elapsed times as short as 5s. This undesirable situation can be prevented by increasing the pouring temperature, by preheating the pipe, or by increasing the inlet pressure. On the other hand, Fig. 8 shows a negligible solidification and blockage for 1000K of pipe wall temperature, even for 10s of elapsed time.

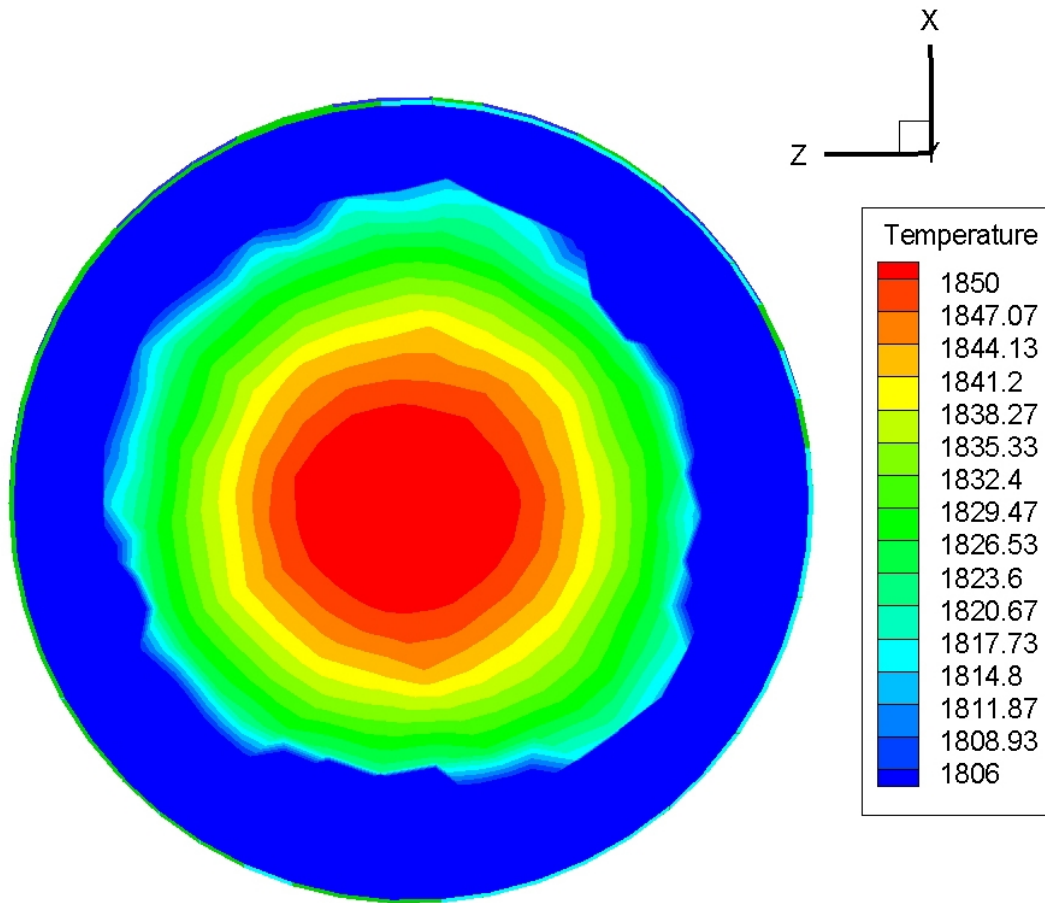


Fig. 4. Cross view of temperature contours (K) at the pipe exit after 5s from the start of pouring. Pipe wall temperature of 300K

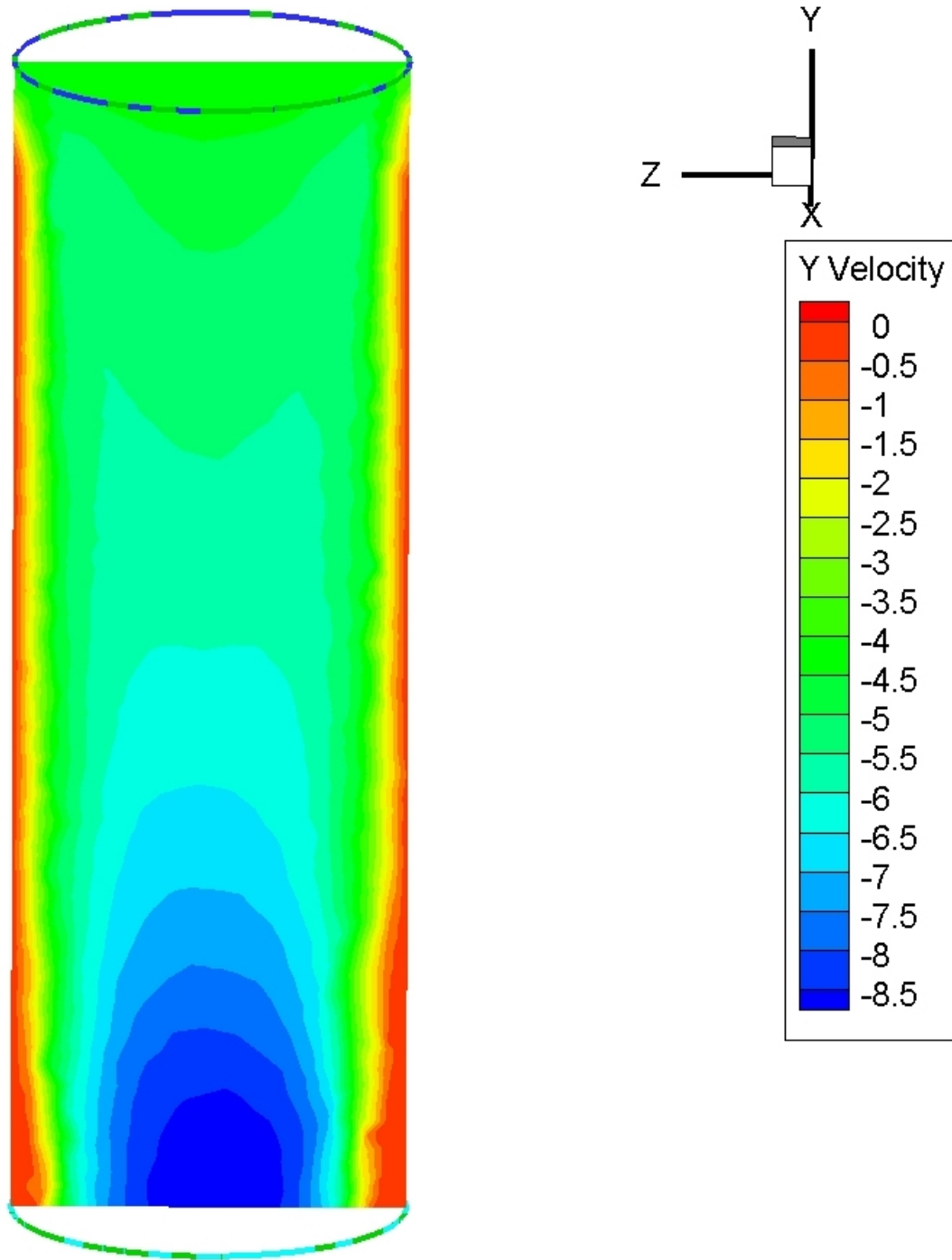


Fig. 5. Contours of the vertical component of velocity (m/s) after 5s of elapsed time. Pipe wall temperature of 300K

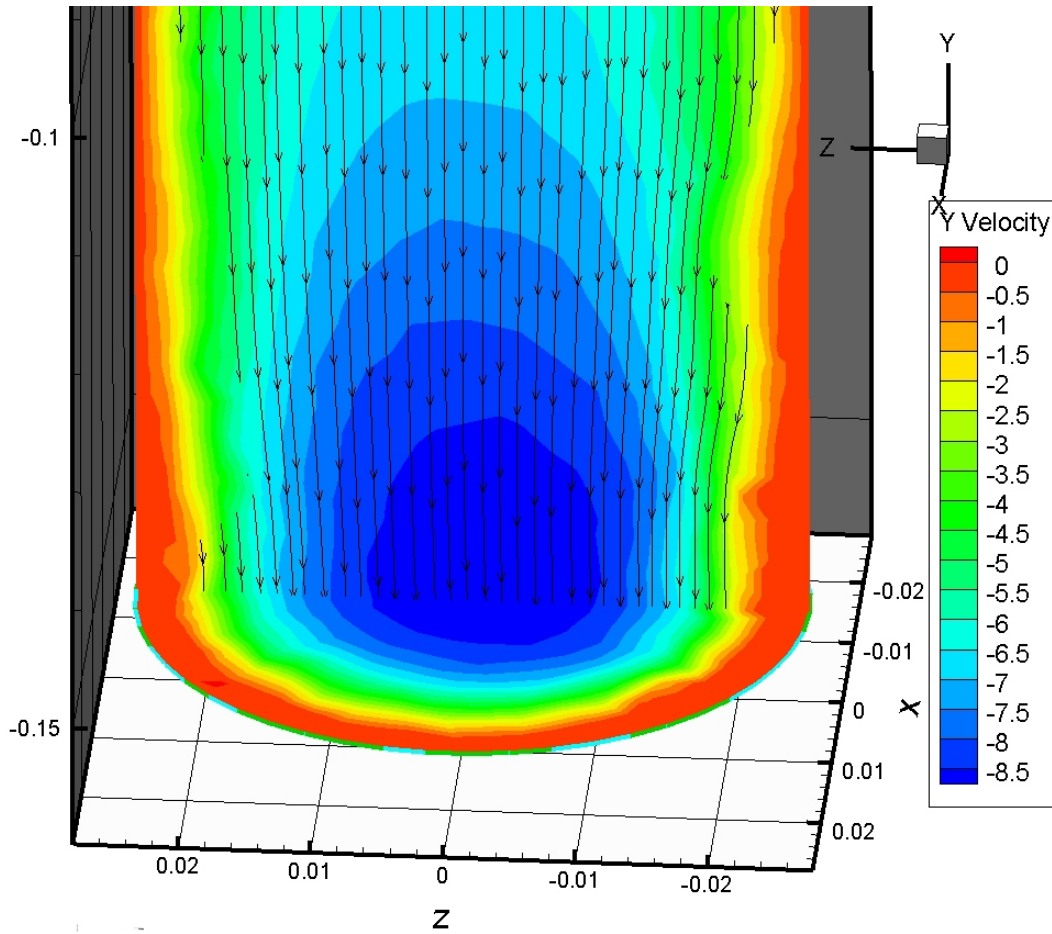


Fig. 6. Contours of the velocity vertical component (m/s) after 5s of elapsed time at the pipe exit. Pipe wall temperature of 300K

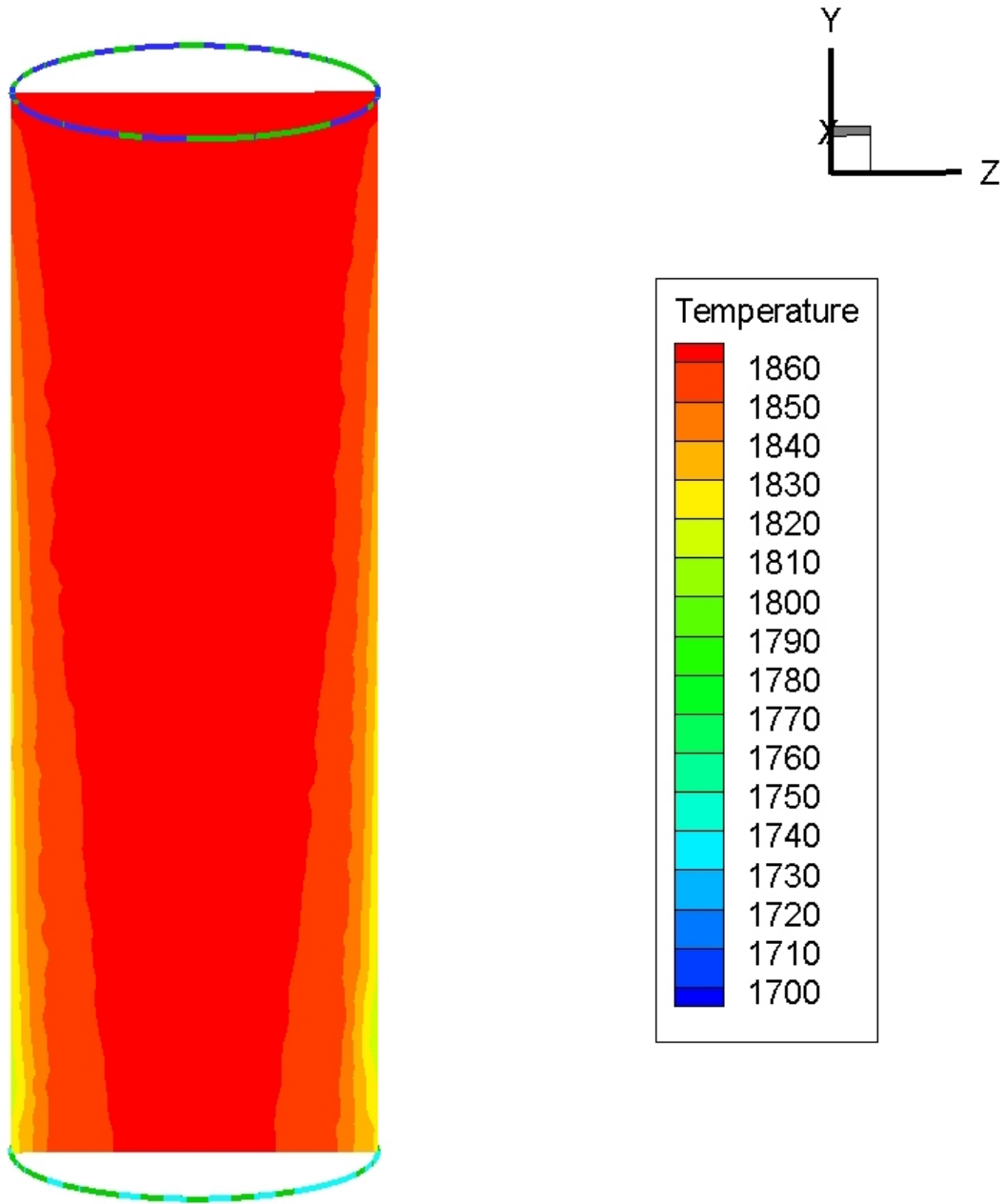


Fig. 7. Temperature contours (K) after 5s of elapsed time for a pipe wall temperature of 1000K

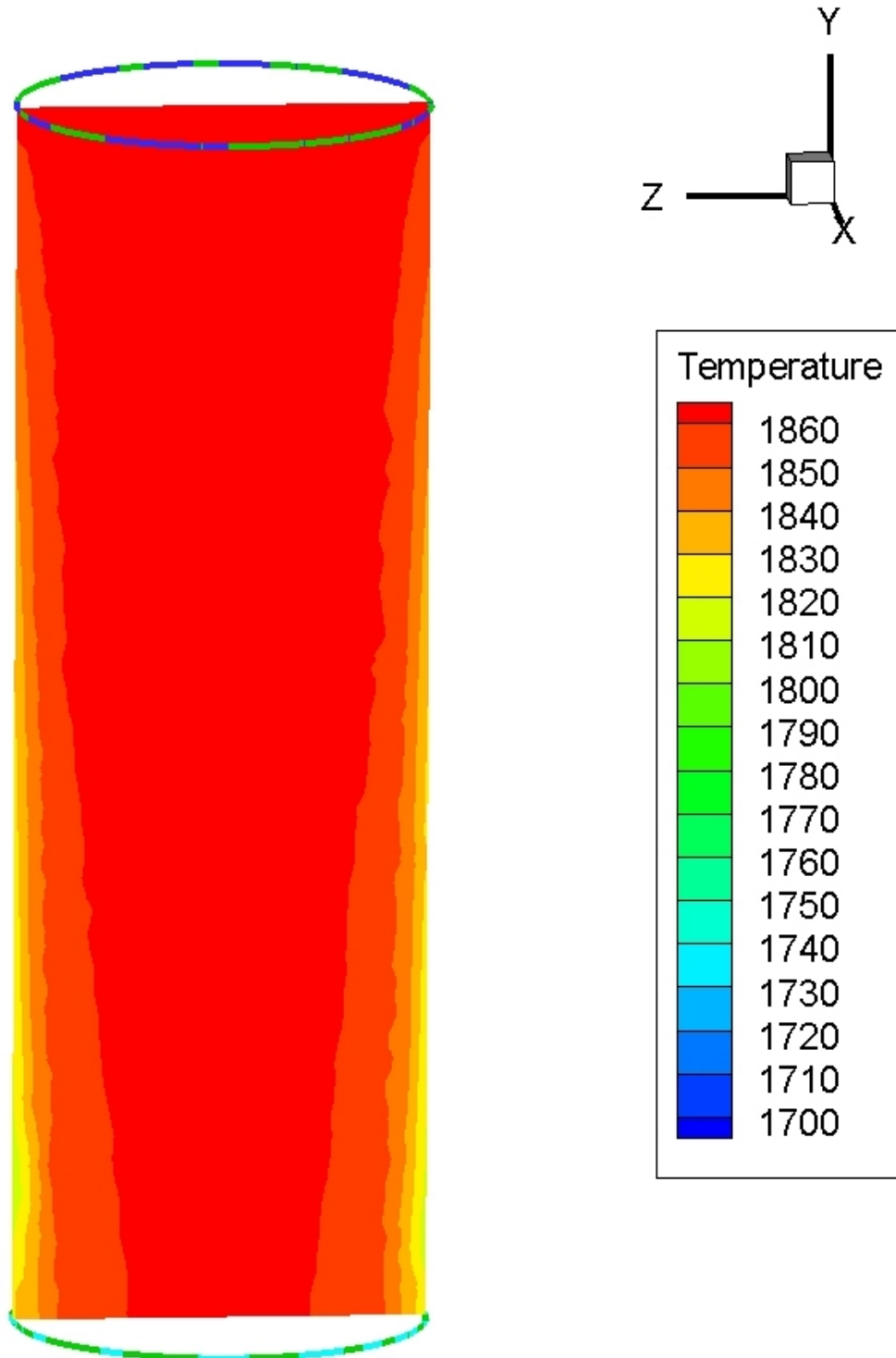


Fig. 8. Temperature contours (K) after 10s of elapsed time for a pipe wall temperature of 1000K

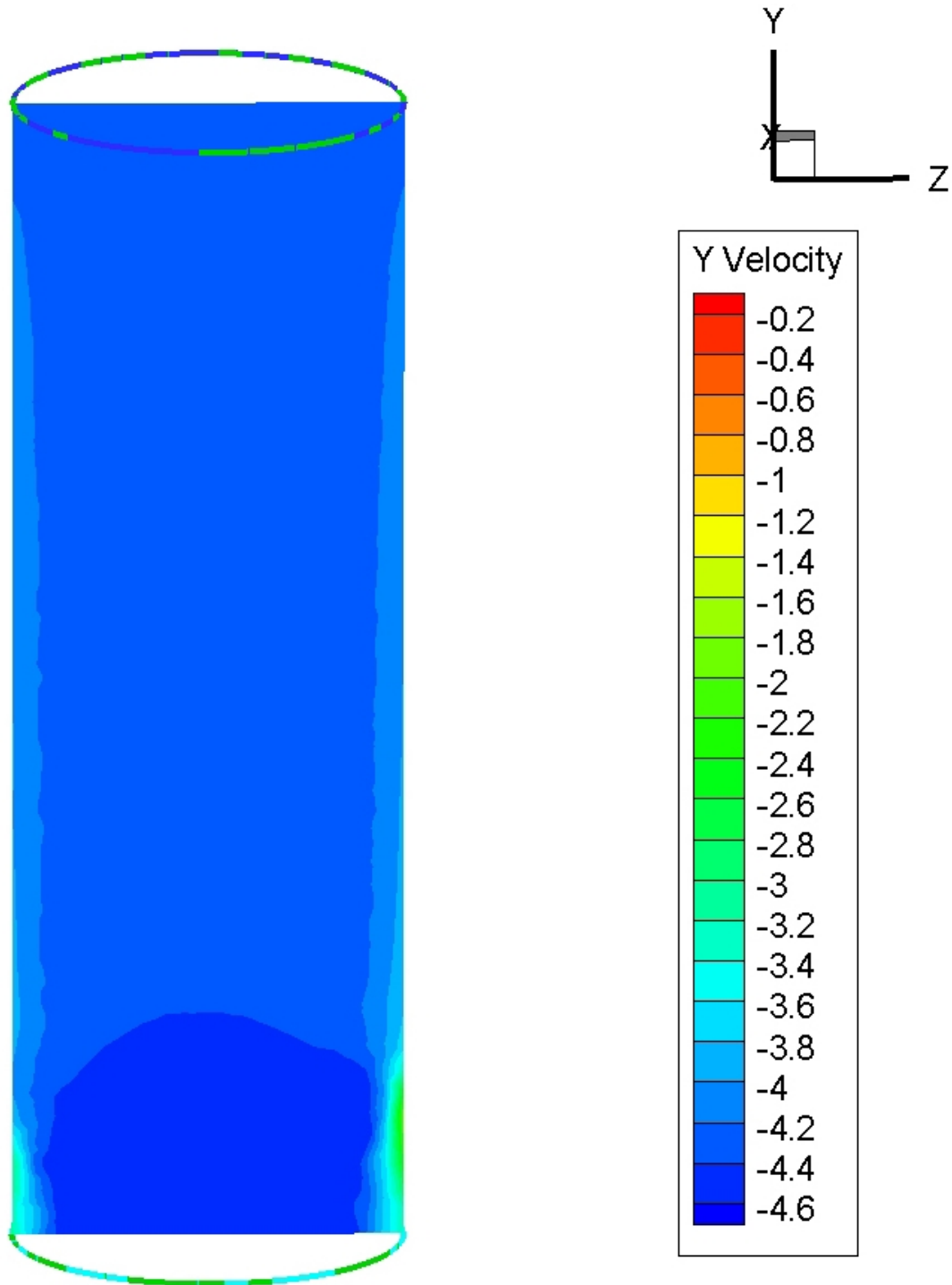


Fig. 9. Contours of the vertical component of velocity (m/s) after 5s of elapsed time for a pipe wall temperature of 1000K

7. CONCLUSION

It was studied the effect of the pipe wall temperature on the internal velocity, temperature and solidification of molten iron during the casting of pure iron through a pipe using the Computational Fluid Dynamics technique.

- (i) A pipe wall temperature of 300K promotes early solidification and blockage and yields strong internal gradients of velocity and temperature.
- (ii) A pipe wall temperature of 1000K prevents solidification and promotes a more homogeneous flow and temperatures contours. For fast pouring times no blockage is expected.
- (iii) The pipe wall temperature is a very critical variable in the solidification and blocking phenomena during the pouring through pipes of molten iron; therefore this variable must be carefully controlled during the pouring process.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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