Heat transfer and solidification of molten iron in a pipe

Abstract

The effect of the pipe wall temperature on heat transfer and 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. 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.

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

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 freezing 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 freezing 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 freezing 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 smalls rates of change of the frozen layer. In [3] a mathematical model which considers natural convection is presented; the minimun pressure drop required to prevent the pipe blockage is determined. A numerical analysis of the transient freezing 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 become negligible. Blockage of the pipe depends on the pressure inlet and on the inlet temperature. In [5] is numerically tackled the problem of transient solification and blockage of a molten pure metal in a cold runner. 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. These authors analyze the influence of the diameter and length of the runner and the inlet and wall temperatures on the crust freezing rate and runner blockage. They report that the runner diameter is the most critical variable for runner blockage.

The transient freezing 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 freezing zone in which the cold metal becomes frozen. 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] is presented a criterion to predict whether certain system under laminar flow will present blockage. A comparison is made with previous experimental results for freezing of water, and good agreement is exhibited. In another paper [8], the freezing under turbulent flow is analyzed, and predictions of blockage time are presented for systems with Re numbers between 2000 and 10000 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 frozen crust thickness for certain values of inlet Re number and the coolant temperature are reported. In accordance to this work, if the inlet Re number is increased, the coolant temperature needed to start the oscillatory behavior is also increased. Transients which do not yield blockage are studied analytically studied in [11]. The theoretical results of this work are compared with experimental ones and good agreement is reported for small frozen crust thickness. For large crust 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 frozen crust 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 solidified layer thickness and metal flow rate, and experimental verification of the mathematical model is reported using molten tin. In work [14] is addressed the transient freezing 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 amd solved using the the separation of variables method.

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. Reynolds Stress Model is employed to simulate the turbulence, and in order to avoid the complexity of the mushy zone, pouring of pure iron is considered.

2 Mathematical Model

2.1 Momentum transfer and mass balance

Internal solidification in pipes is a complex problem given that in this process coexist fluid flow, mass transfer, heat transfer and phase change. Equations which model the momentum transfer of an incompressible fluid are known as equations of motion, and they are expressed in this way [15]:

$$\rho\frac{D\mathbf{v}}{Dt} = -\nabla p + \mu\nabla^2\mathbf{v} + \rho\mathbf{g} \tag{1}$$

where ρ is the molten metal density, t is time, $\mathbf{v}$ is the velocity vector, p is the pressure, μ is the molten metal viscosity and $\mathbf{g}$ 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 that two-equations models such as the k-ϵ model.

RSM is derived from the motion equations and the Reynolds stress tensor [16]. 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 coordinate system, respectively.

2.2 Heat transfer and solidification

For heat transfer and solidification the following version of the energy equation is employed [17]:

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

where H is the molten metal entalphy, 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

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

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

where D is the pipe diameter. Besides, inlet temperature is the pouring temperature.

3 Numerical Solution

Mathematical model is numerically solved by means of Fluent CFD software. 3D transient simulations are carried out using a 56 000 element mesh, a time step of 1x10-4 s and the Pressure Implicit Splitting Operation (PISO) algorithm for pressure-velocity coupling [17]. Pure iron, whose properties are taken from [5], is considered as molten metal in the numerical simulations to avoid the mathematical complexity of the mushy zone. A pipe with 0.05 m of internal diameter and 0.15 m high was assumed, see Fig. 1. Pipe wall temperature is considered as critical variable for heat transfer and solidification. Two pipe wall temperature are considered, namely 300 and 1000 K. Pouring temperature is kept constant at 1860 K.

4 Results of simulations

4.1 Pipe wall temperature of 300 K

Fig. 2 shows temperature contours 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 (1811 K), therefore this region contains just solidified metal. At the end of the pipe, i.e. a height of 0.15 m, the solidified layer is approximately 0.007 m thick. Fig. 3 shows a cross view of the temperature distribution at the pipe exit after 5s of elapsed time. As in Fig. 2, blue zone contains the frozen metal. Approximately 60 percent of the initial flow area remains free, whereas the rest is blocked by the solidified metal. In this case a significant blockage is exhibited by the pipe.

In Figs. 4 and 5 are depicted some contours of the vertical component of velocity after 5 s from the start of pouring. Fig. 5 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 pipe exit can be fully blocked.

4.2 Pipe wall temperature of 1000 K

Figs. 6 and 7 show the contours of temperature after 5 and 10 s, respectively, from the start of pouring for a pipe wall temperature of 1000 K. Both figures are similar. For the elapsed times considered, no significant zones with temperature below the iron freezing temperature are observed. This means that no internal solidification is present, at least during the first 10 s of elapsed time. In Fig. 8 is depicted the vertical component of velocity after 5s for 1000 K of pipe wall temperature. A very homogeneous radial distributions of temperature and vertical velocity is appreciated for this pipe wall temperature. Given that internal solidification is negligible in this case, no significant drops in velocity are present for the considered pipe wall temperature.

4.3 Remarks

In accordance to Fig. 3, pipe wall temperature of 300 K causes fast freezing of molten iron for a pouring temperature of 1860 K; a result of this is that a significant blockage is exhibited for elapsed times as short as 5 s. This undesirable situation can be prevented by increasing the pouring temperature, preheating the pipe, or increasing the inlet pressure. On the other hand, Fig. 7 shows negligible freezing and blockage for 1000 K of pipe wall temperature, even for 10 s of elapsed time.

5 Conclusions

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

(i) Pipe wall temperature of 300 K promotes early solidification and blockage, and yields strong internal gradients of velocity and temperature.

(ii) Pipe wall temperature of 1000 K prevents freezing and promotes a more homogeneous flow and temperatures contours of molten iron in the pipe. For fast pouring times no blockage is expected.

(iii) Pipe wall temperature is a very critical variable in the solidification and blocking phenomena during the pouring through pipes of molten iron, therefore it must be carefully controlled.

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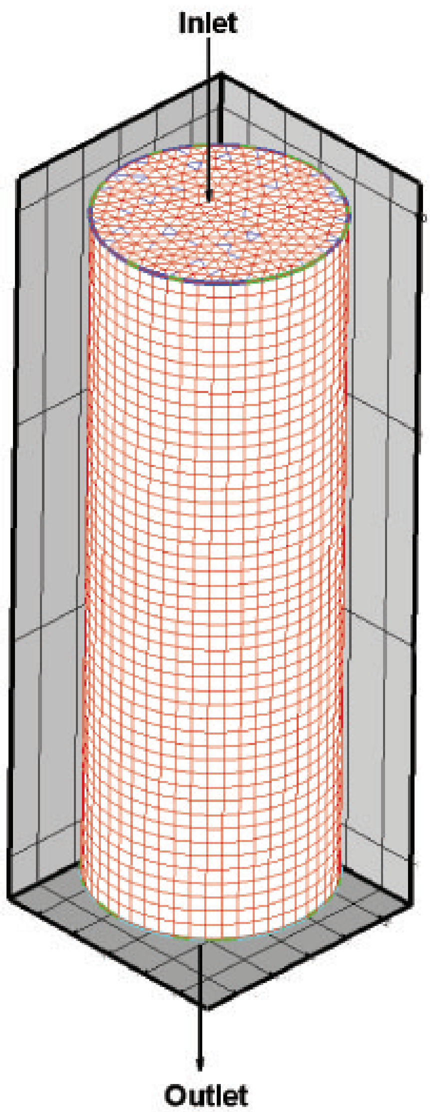

Figure 1: The pipe.

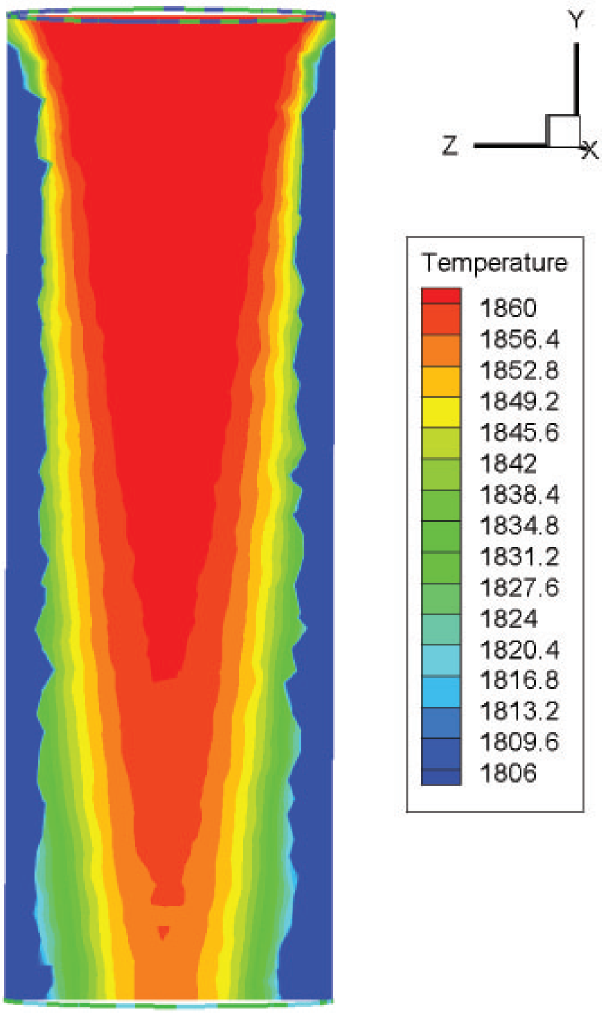

Figure 2: Contours of temperature (K) after 1 s of elapsed time for pipe wall temperature of 300 K.

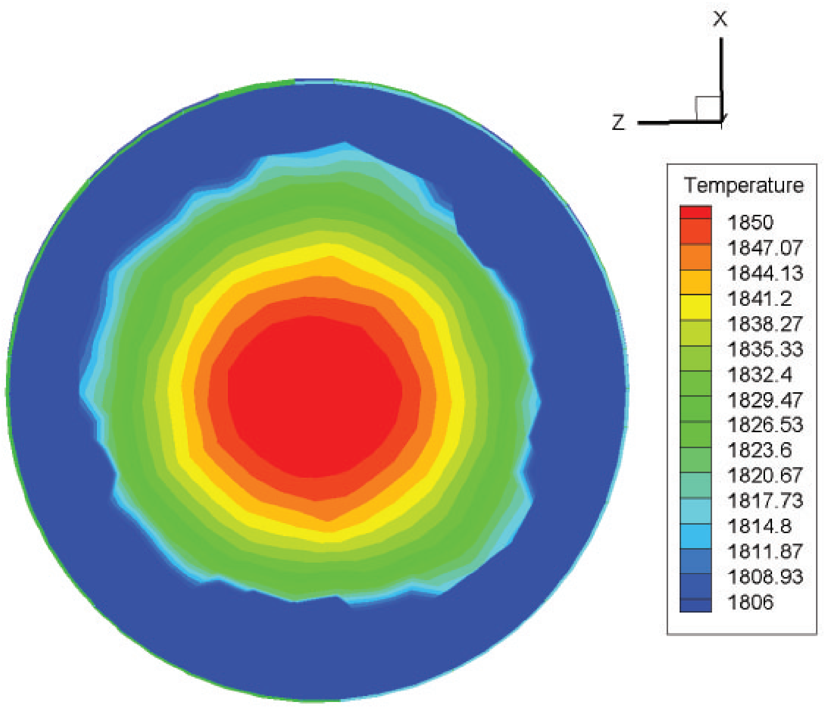

Figure 3: Cross view of temperature contours (K) at the pipe exit after 5 s from the start of pouring. Pipe wall temperature of 300 K.

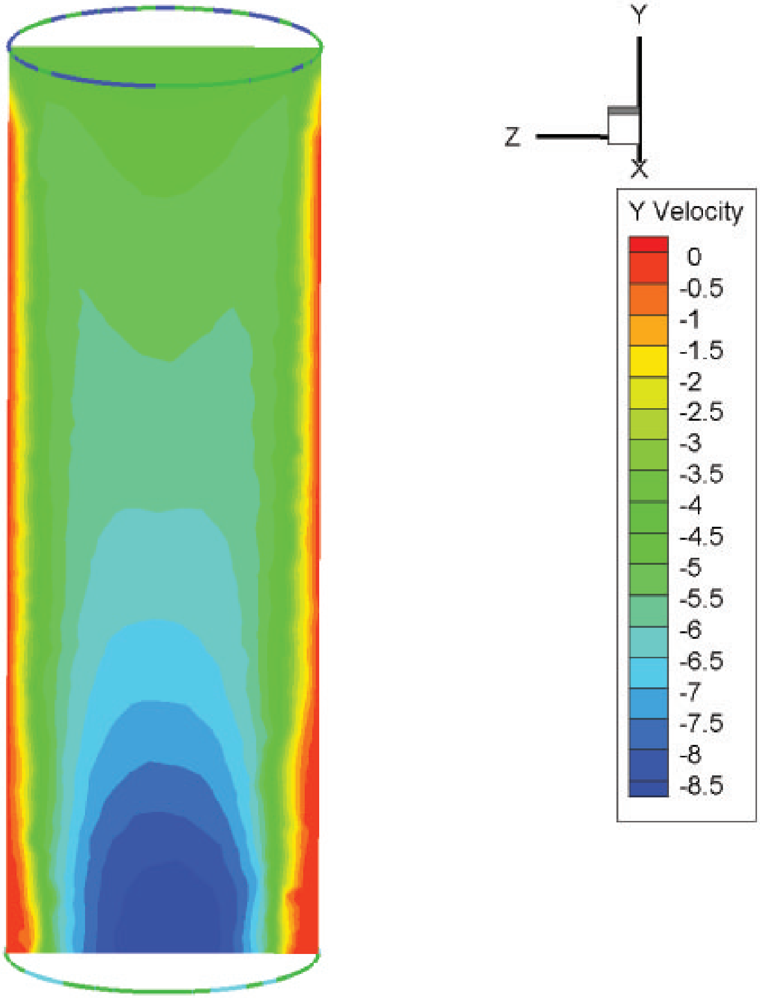

Figure 4: Contours of the vertical component of velocity (m/s) after 5 s. Pipe wall temperature of 300 K.

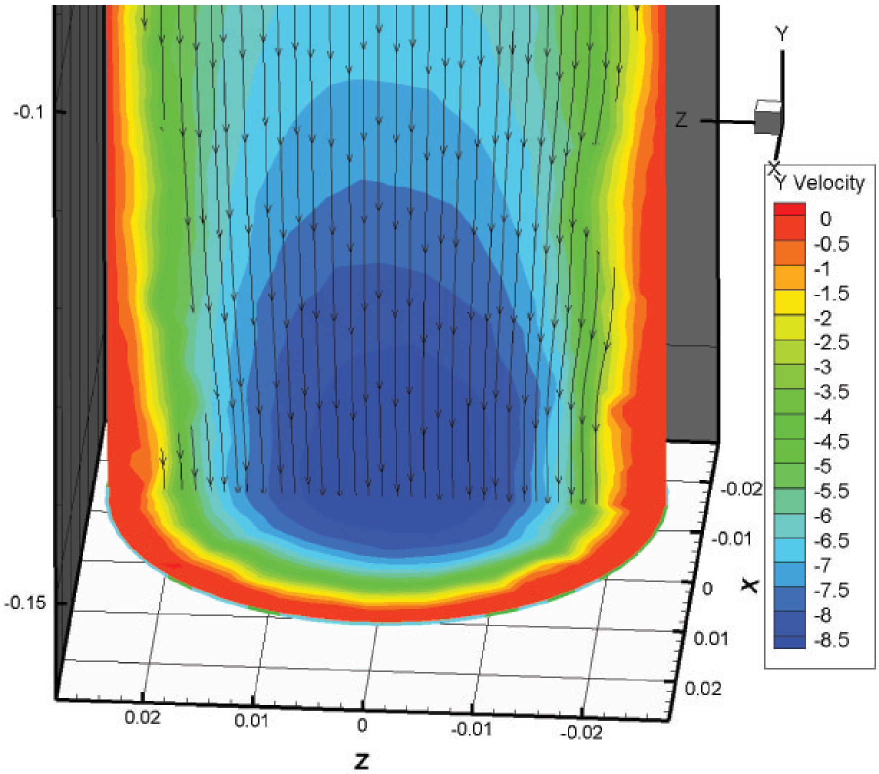

Figure 5: Contours of the velocity vertical component (m/s) after 5 s at the pipe exit for pipe wall temperature of 300 K.

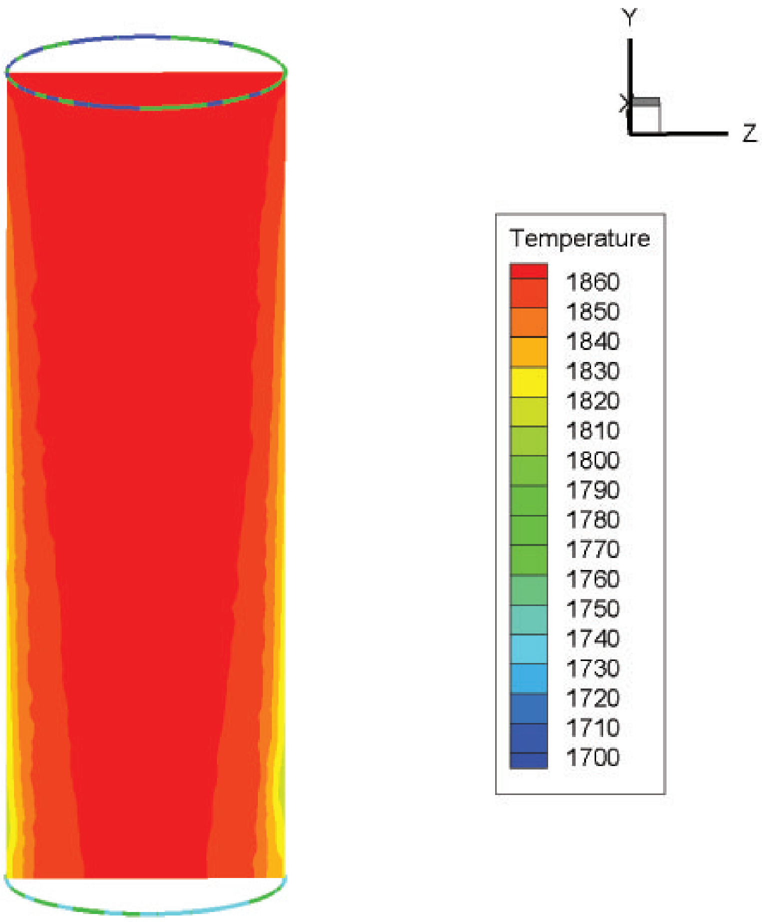

Figure 6: Temperature contours (K) after 5 s for pipe wall temperature of 1000 K.

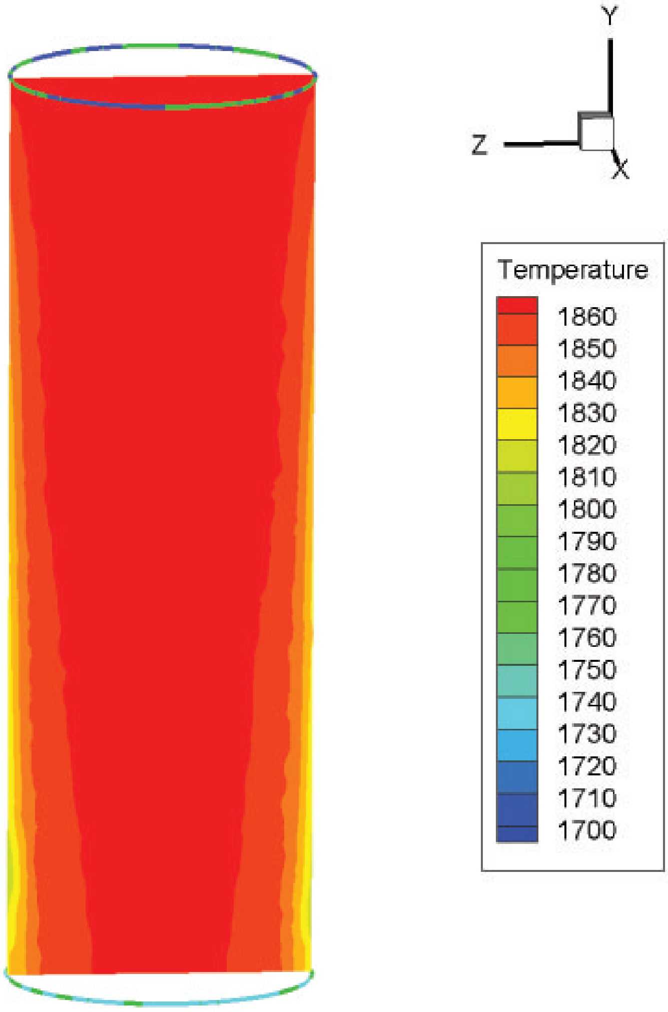

Figure 7: Temperature contours (K) after 10 s for pipe wall temperature of 1000 K.

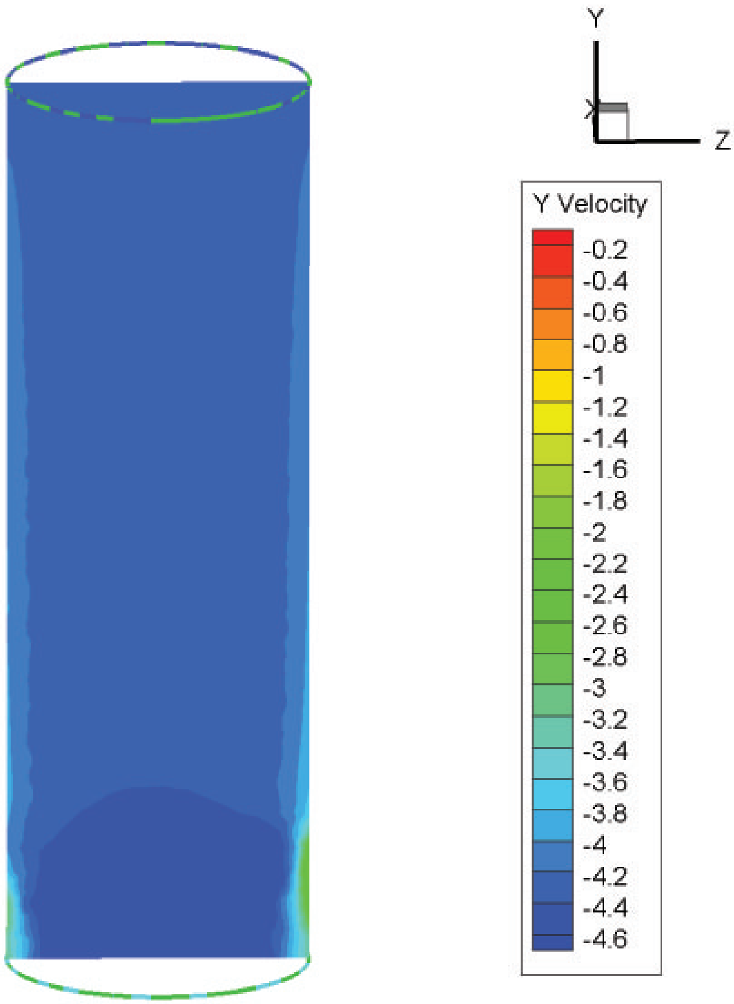

Figure 8: Contours of the vertical component of velocity (m/s) after 5 s for pipe wall temperature of 1000 K