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Title:

Investigation of using a Porous Media Approximation for Flow and Heat Transfer Through the Nuclear Materials Storage Facility Drywell Array

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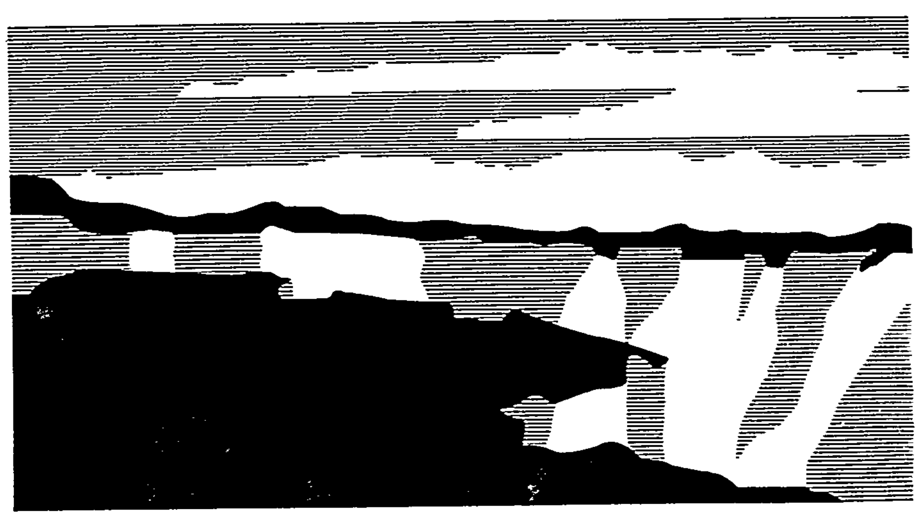

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INTRODUCTION

The Nuclear Materials Storage Facility (NMSF) is being renovated to provide a safe and secure long-term facility at Los Alamos National Laboratory to store nuclear materials. The concept for storage uses vertical tubes that are called drywells that have nuclear bearing canisters inside the tubes. The NMSF facility may use up to 370 of these tubes containing up to 10 canisters producing 15 W each. Analysts at the Laboratory wish to use CFD computer codes to predict the flow and thermal effects of air flow through the facility and the tube array. However, the complexity and large number of storage tubes precludes modeling the facility in enough detail to resolve the boundary layers around each and every tube. Therefore, certain approximations have to be made. A major approximation that has been used in this modeling effort has been to simulate the array of tubes as a porous media. The assumption in the use of porous media is that the resistance of the drywells can be accounted for in a general way.

The purpose of this study is to evaluate the suitability of the porous media approximation for modeling the tube array in the NMSF. In this study we will compare porous media models results with results from models that resolve the boundary layer around tubes. Finally, we offer a compromise modeling approach to address with this problem.

NUMERICAL METHODS

The numerical method used in this study is the commercial CFD computer program CFX 4.2. The CFX code was developed by Harwell Laboratory in Oxfordshire, United Kingdom and is marketed by AEA Technology. CFX is a multi-block, finite volume CFD computer code that simulates both fluid flow and simultaneous heat transfer. For the study reported on here a Silicon Graphics Indigo II machine with 250 MHz, 256 MB RAM, and two 4 GB SCSI hard drives.

The primary capabilities of the code for these studies were use of its ability to simulate three- dimensional and turbulent flow, convection heat transfer, radiation heat transfer, body fitted grids, incompressible flow with a Boussinesq approximation ,buoyant and porous media flow.

MODELS

Porous/non-porous models - In this study, ten tubes in one of the four rows of the facility model were chosen for the comparison. Figure 1 shows these ten tubes and the porous media transformation into several different models. The top figure shows the actual geometry modeled with the 18 in diameter tubes. Symmetry lines are chosen between each tube row. Moving down the figure, the second drawing shows the entire row filled with porous media. This is one of the models used for the comparative studies and is the model that has been used in earlier studies of the NMSF. Again, moving down Fig 1 gives a third model with the storage tubes separated from the air on each side of the tubes. Finally, using symmetry, the model is transformed into a two- block model with one block representing the storage tubes and the other block representing the open air between the tubes.

Figure 2 shows two models. Fig- 2a shows a model that can resolve the boundary layers around each individual tube and we refer to it as a discrete model. Figure- 2b shows a two-block approximation of this model and is used in the later stages of this study. In summary, the modeling effort will be done using a porous media model with the heat and flow resistance distributed in various regions and the discrete model shown in Fig- 2a. We will compare the flow magnitudes and temperature distributions for several boundary conditions.

Heat Distribution - 150 Watts per drywell was used in the study. In addition, the heat was assumed to be distributed uniformly and was input to the code as a surface heat flux for the discrete model and as a volumetric heat source for the porous media model.

Grid Structure - The total number of cells to grid the porous media and discrete model was 50,000 and 250,000 respectively. This illustrates the need for many additional cells when each tube is to be gridded individually.

Porosity – The CFX code requires that the porosity of the porous medium be specified as a ratio of the free fluid volume to the total porous media volume.

Porous Media Resistance - When porous media is used it is necessary to approximate the flow resistance. The CFX computer code needs input on the body force term to adjust for the geometry of the flow. We use a reference that includes formulas for hydraulic resistance by Idelchik (1). The formulation used is for an array of in-line tubes where the resistance formula for Reynolds Numbers between $3*10^3$ and 10^5 is

$$K = 1.8\ (S_1/d_{out} - 1)\text{-}0.5{*}R_{em}^{-0.2}Z_r, \quad (1)$$

where

S_1 = transverse pitch

d_{out} = tube diameter

R_{em} = Reynolds Number

Z_r = number of rows

To apply resistance properties to the porous model, the resistance speed factor must be calculated for CFX input. The following formulation is used

$$RSF = K\rho/2\nabla L \quad (2)$$

Where

RSF = resistance speed factor

ρ = fluid density

K = loss coefficient for in-line tube arrays

∇L = resistance length

COVERGENCE CRITERIA

A number of steps were taken to determine convergence and credibility of the results produced in CFX. A model is said to have converged once the solution has reached a steady unchanging state. The convergence of a model is first determined by examining the residuals. Secondly, convergence is determined by examining how closely the mass and energy is balanced when summed over the whole model. The energy balance should not have an error of more than 5- 10 %.

RESULTS

Symmetry Checks - Before comparisons of the porous and nonporous calculations were made, several calculations were performed to ensure that the problems were being set up correctly. By imposing zero pressure boundary conditions on the inlet and outlet ends of the models we expect to observe symmetrical temperature and velocity distributions. The discrete model (ten tubes modeled including the boundary layer) with and without radiation were calculated. These results are shown in Figs. 3 and 4. Notice that both temperature and velocity are symmetrical. In the model with radiation, a heat-up of the floor can be observed. The model that includes radiation shows a slightly lower buoyant velocity and a lower maximum temperature of 1.2 °C.

The porous media calculations are shown in Figs. 5 and 6. Figure 5 shows the results when the heat is distributed throughout blocks 1 and 2. The results shown in Fig. 6 shows results where the heat is distributed in block 2 only. Refer to Figs. 1 and 2 for orientation of block 1 and 2. As with the discrete model, the temperature and velocity distributions are symmetrical. Both calculations show that the velocities are similar, but the temperature is higher for the case with heat distributed in only block 2. We notice that the maximum velocity in the porous media model is lower than the discrete model (0.48 m/s compared to 0.70 m/s).

Forced Inlet Flow – Figure 7 shows the results for the discrete model with an imposed forced flow on the inlet. The flow is from left to right in Fig. 7. The slice shown in Fig. 7 is slightly outside of the tube diameter. Notice that the dominant flow is horizontal rather than vertical. The maximum temperature is 302.3 K and the maximum velocity is 0.63 m/s. The temperature distribution shows a build-up of heat to the right and at the top of the bay model.

Using porous media instead of discrete tubes, the results are quite different and are shown in Fig. 8. The temperature distribution does not show a build-up of temperature in the upper right-hand corner of Fig. 9 as compared with the discrete model in Fig. 8. In addition, the magnitude of the temperature is lower by 5.1 °C. The velocity magnitude is also slightly lower at 0.465 m/s.

A slight improvement can be obtained by distributing the heat in only block 2. These results are shown in Fig. 9. However, the velocity is unaffected and is lower than the discrete model results.

PROPOSED MODELING APPROACH

A procedure that shows some promise is to model the bay with the heat and porous media resistance placed only within longitudinal strips where the tubes are located. This approach offers and open region around the tubes for unrestricted flow, vertical flow in the porous media region and a diffusion of the heat out to the higher flow region between the tubes. Results from this approach are shown in Figs 10 –13. By comparing the vertical slices between the discrete model, shown in Fig. 7, and the vertical slice of the porous media. The model of Fig. 10 shows that the discrete model has a maximum temperature of 302.3 K while the porous media model has a maximum temperature of 301.5 K or a difference of 0.8 °C. The maximum velocities are even closer with o.63 m/s in the discrete model and 0.65 m/s in the porous media model.

Figures 12 and 13 are a series of horizontal slices at several heights in the ten tubes for the discrete and porous media models. Notice the similarity in the velocity profiles between the two models. This similarity is also shown in Fig. 13. Figure 13 depicts the horizontal distribution of temperature down the single row of tubes for both models. Although the selection of the resistance coefficient used in these calculations may have influenced these results, no attempt was made to adjust the coefficients to achieve these results.

CONCLUSIONS

The analysis performed here shows that the approach of representing the entire bay as porous media and distributing the heat throughout the bay is not an accurate way to simulate the bay flow and heat-up. Generally the temperature and velocity magnitudes are under-predicted. Finally an approach using porous media but placing the heat and porous resistance only in strips down the bay may offer some promise in modeling the entire facility.

REFERENCES

1. I. E. Idelchik, Handbook of Hydraulic Resistance, 3rd Edition, CRC Press, 1994

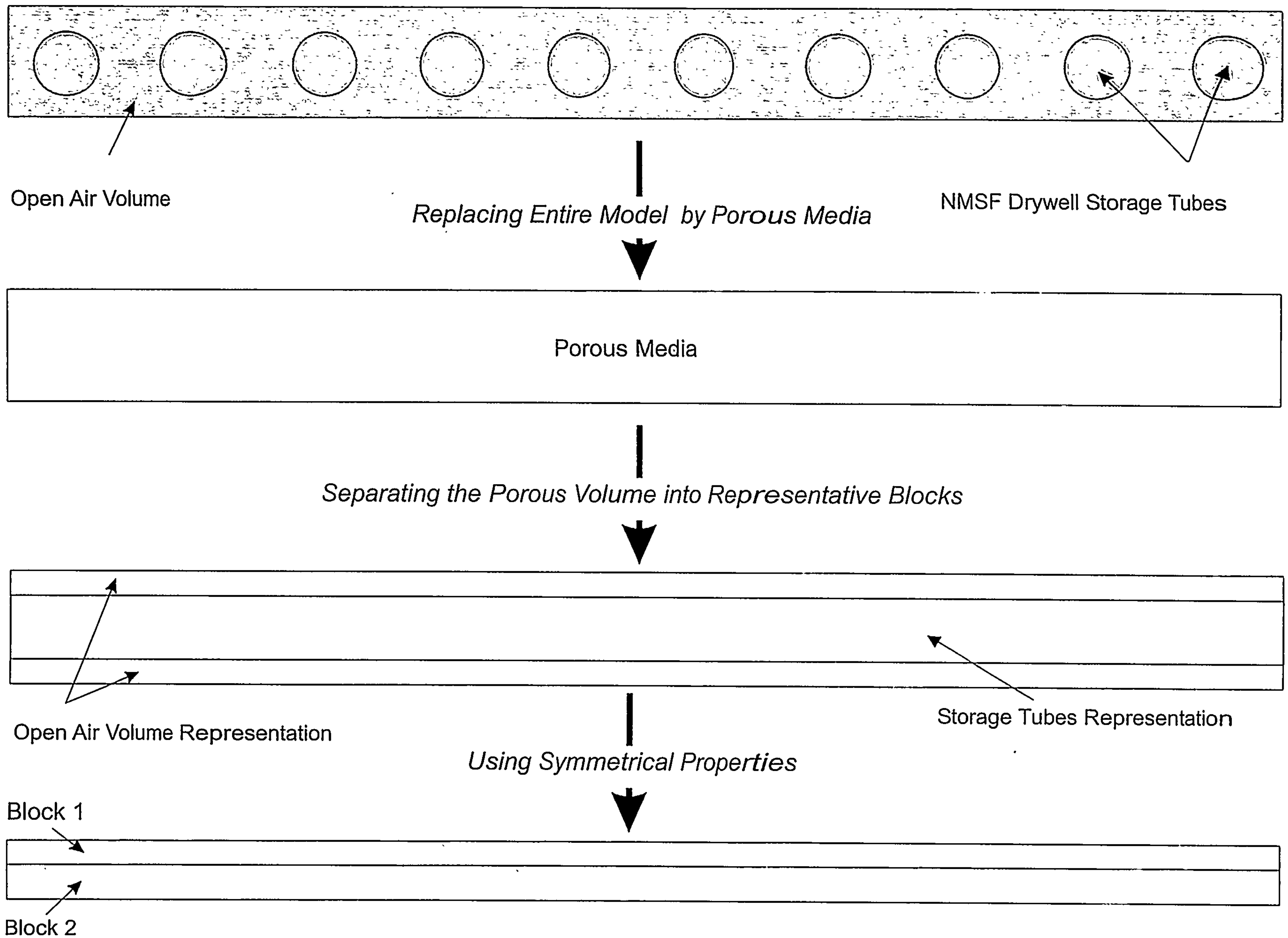


Figure 1. The transformation from the discrete model to the porous media model.

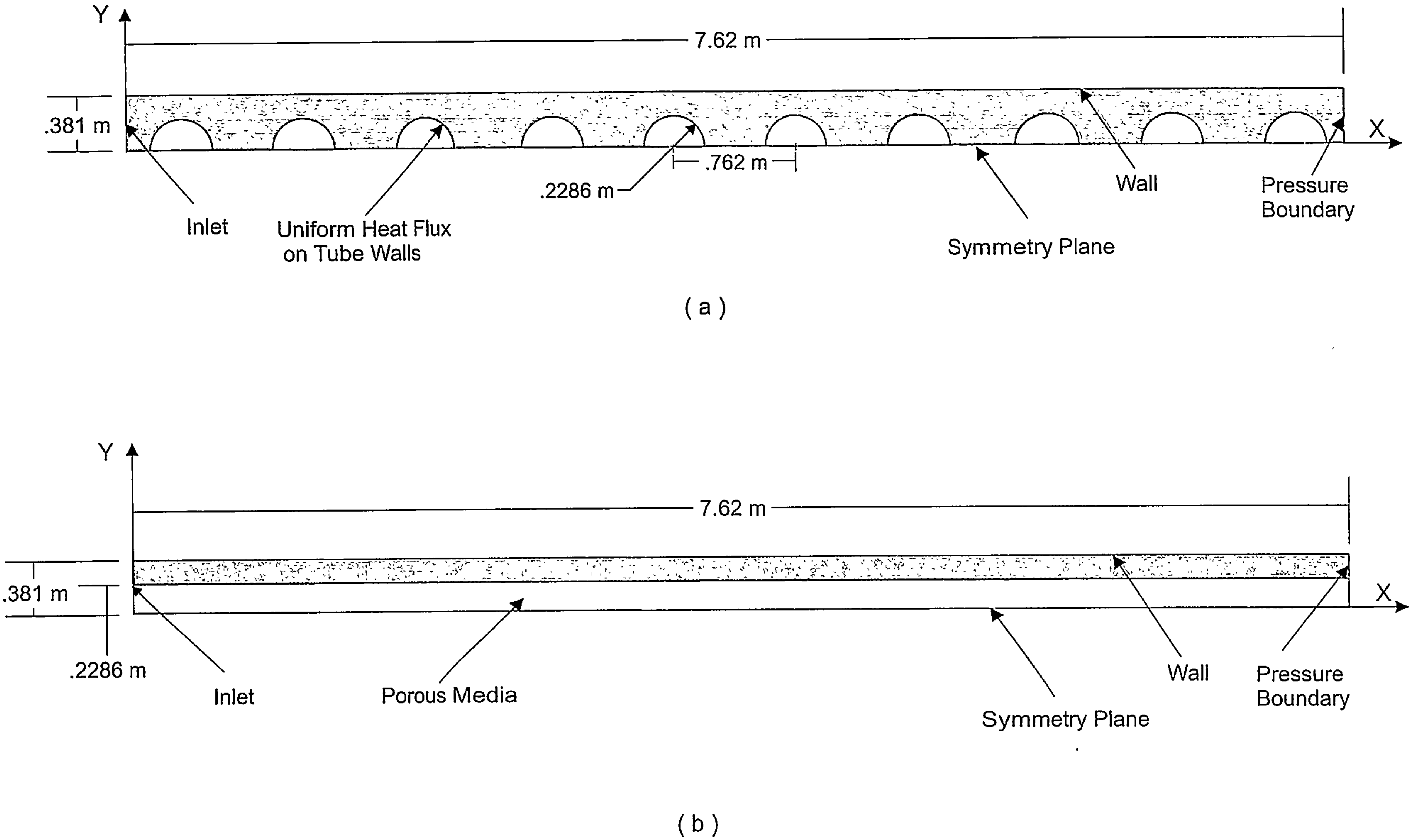


Figure 2. Geometries and boundary conditions for the (a) discrete ten tube model and (b) porous media models.

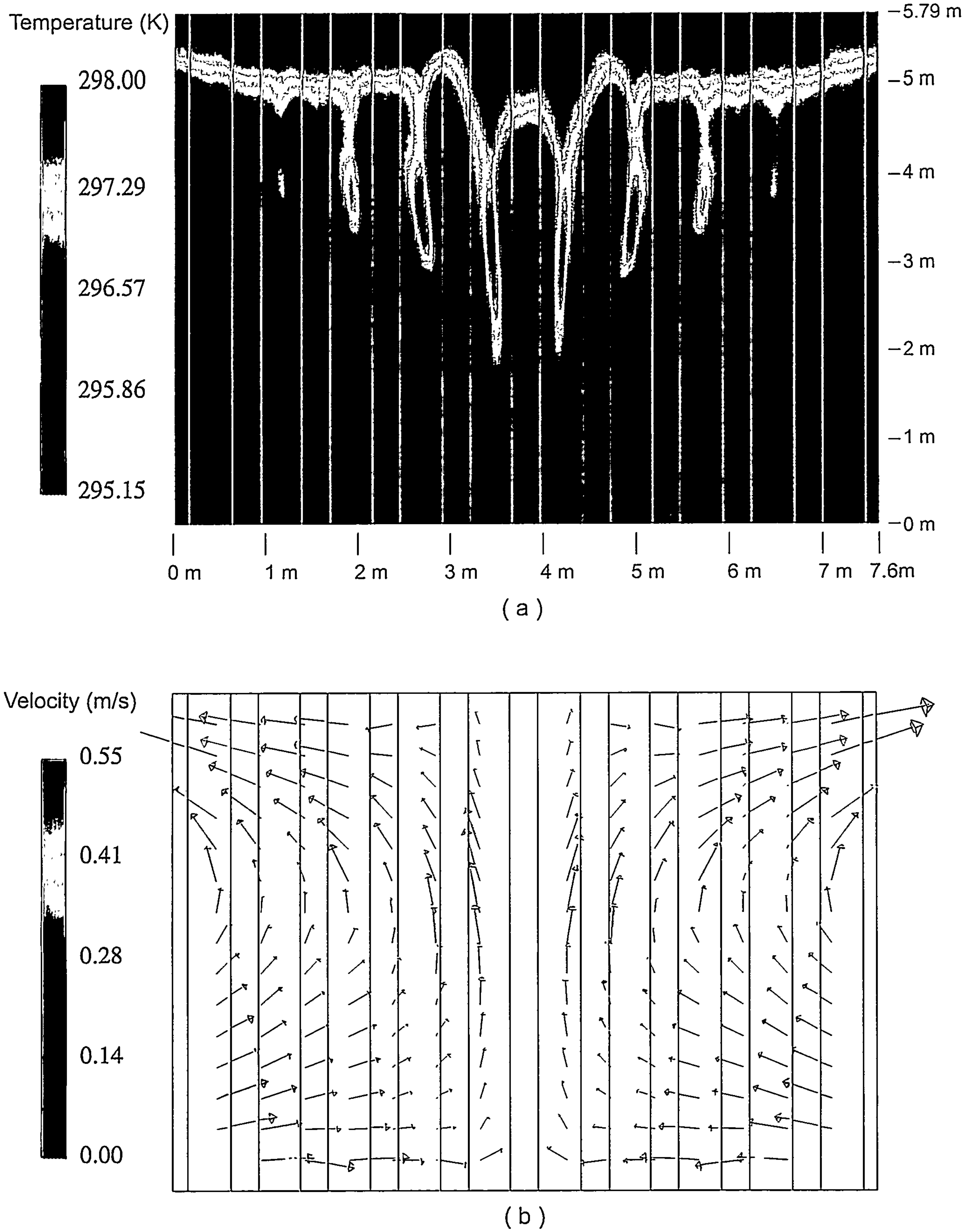


Figure 3. Temperature contour(a) and velocity vector(b) plots for the discrete ten tube model with purely buoyant flow. The model carries a maximum temperature of 304.0 K and a maximum velocity of .70 m/s.

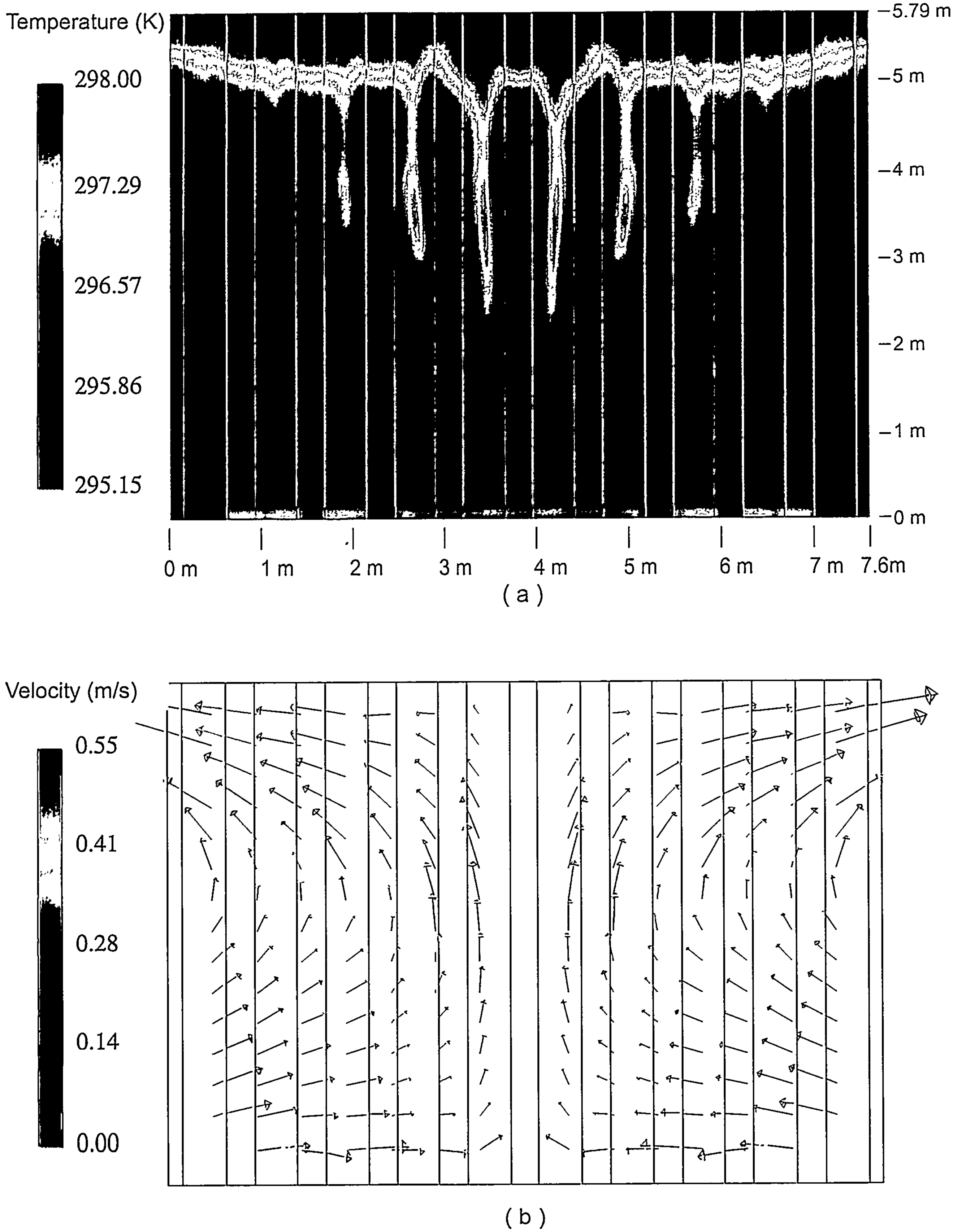
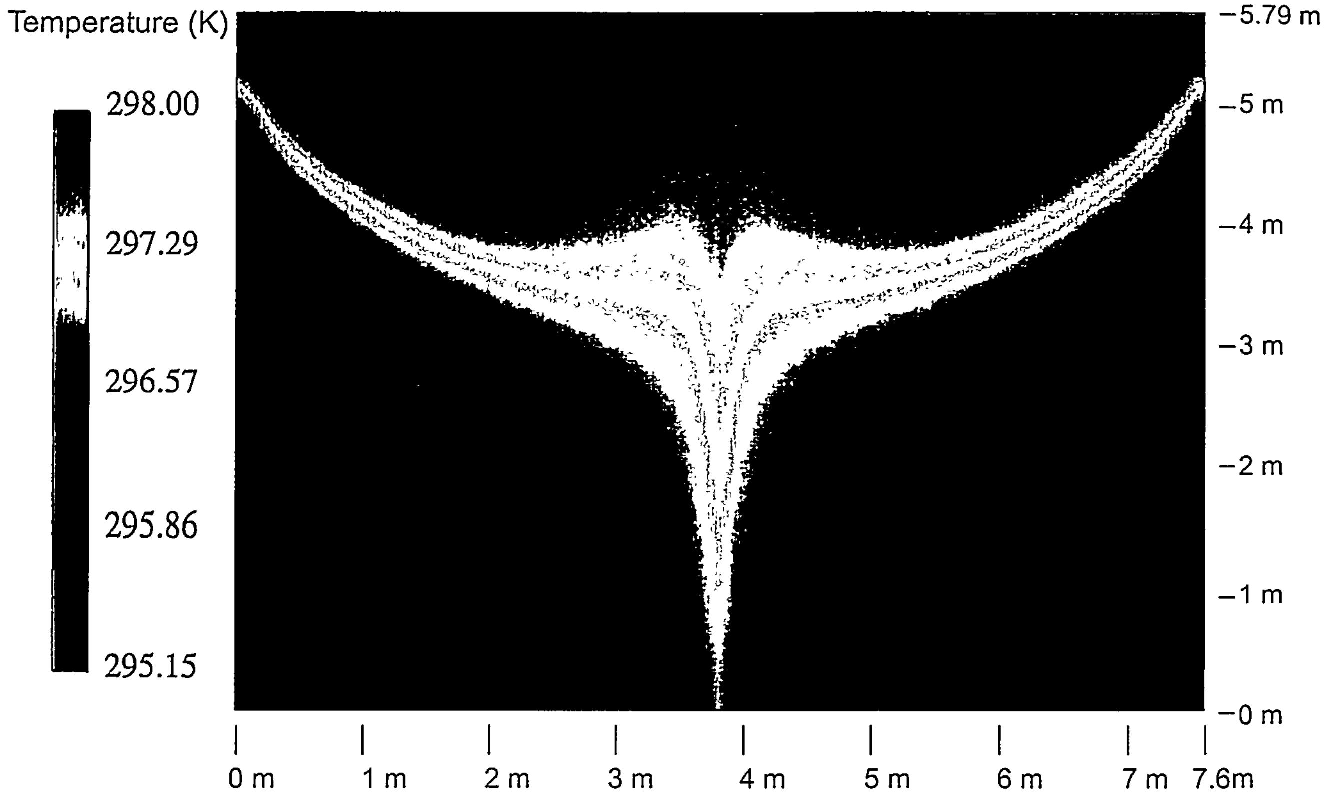
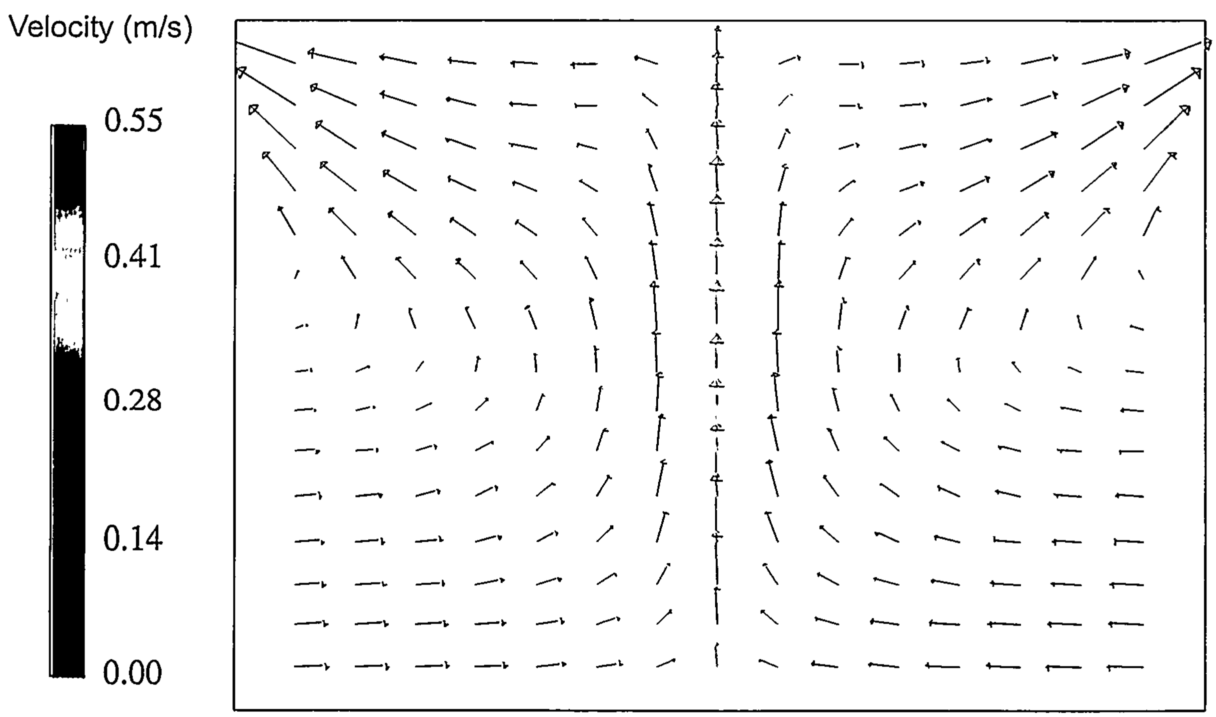


Figure 4. Temperature contour(a) and velocity vector(b) plots for the discrete ten tube model with radiation and buoyant flow. The model carries a maximum temperature of 302.8 K and a maximum velocity of .69 m/s.



(a)



(b)

Figure 5. Temperature contour(a) and velocity vector(b) plots for the fully porous media model with purely buoyant flow. The model carries a maximum temperature of 299.4 K and a maximum velocity of .48 m/s.

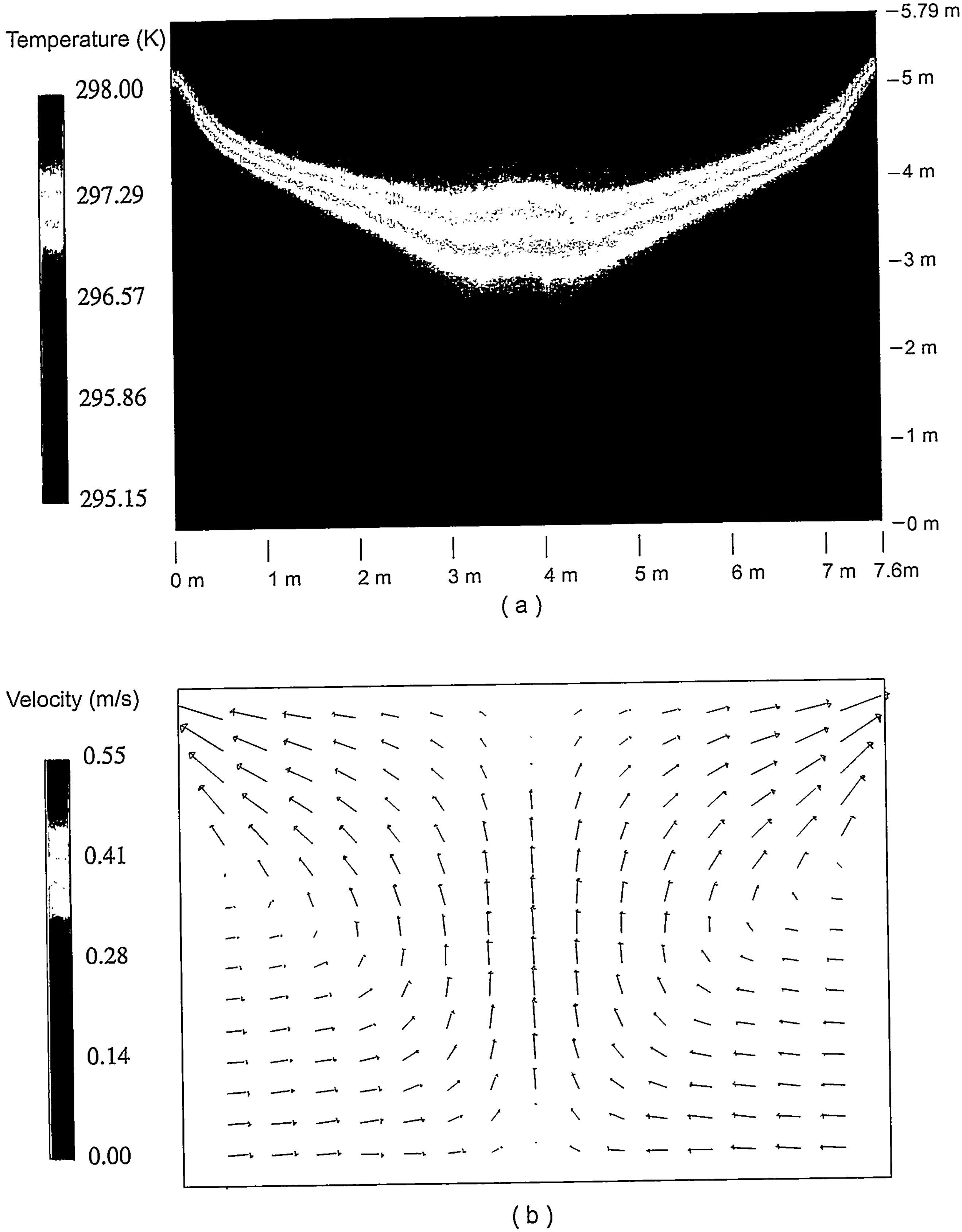
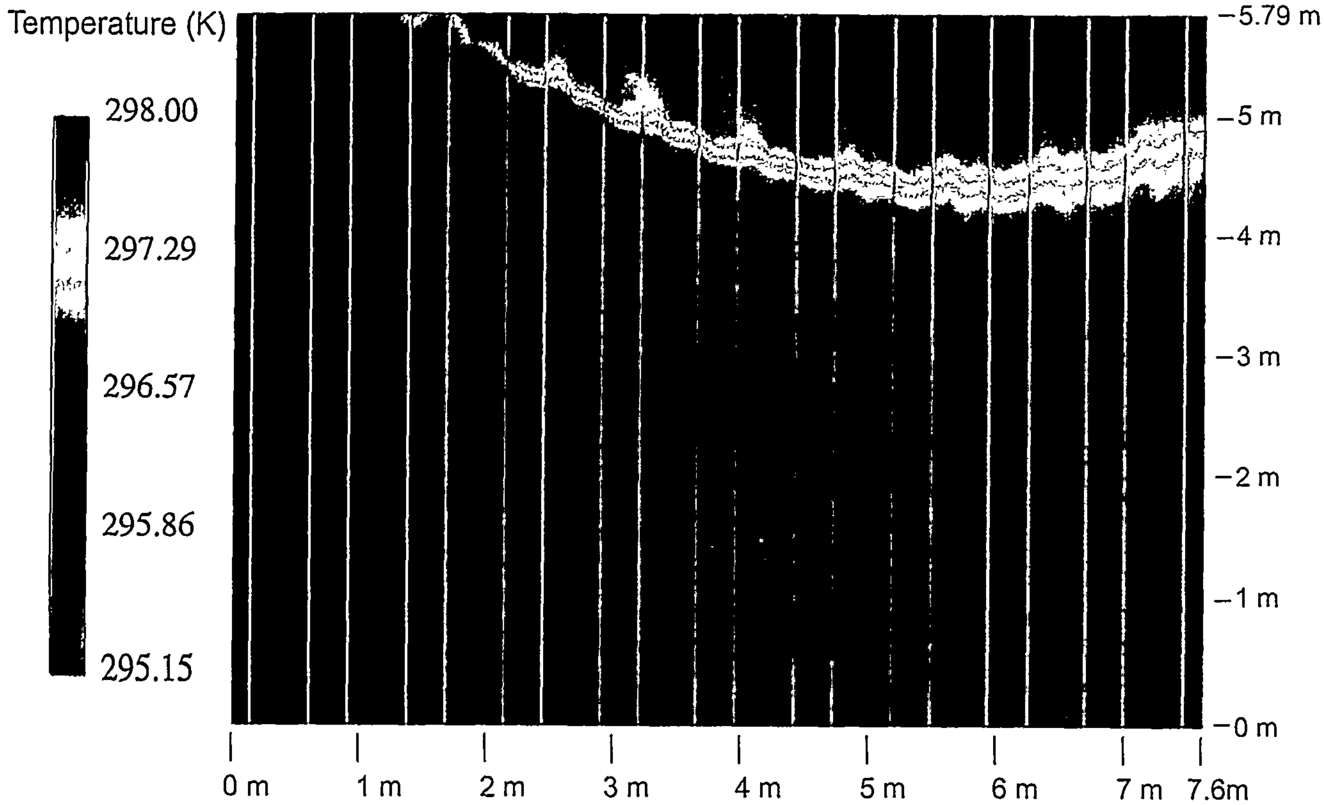
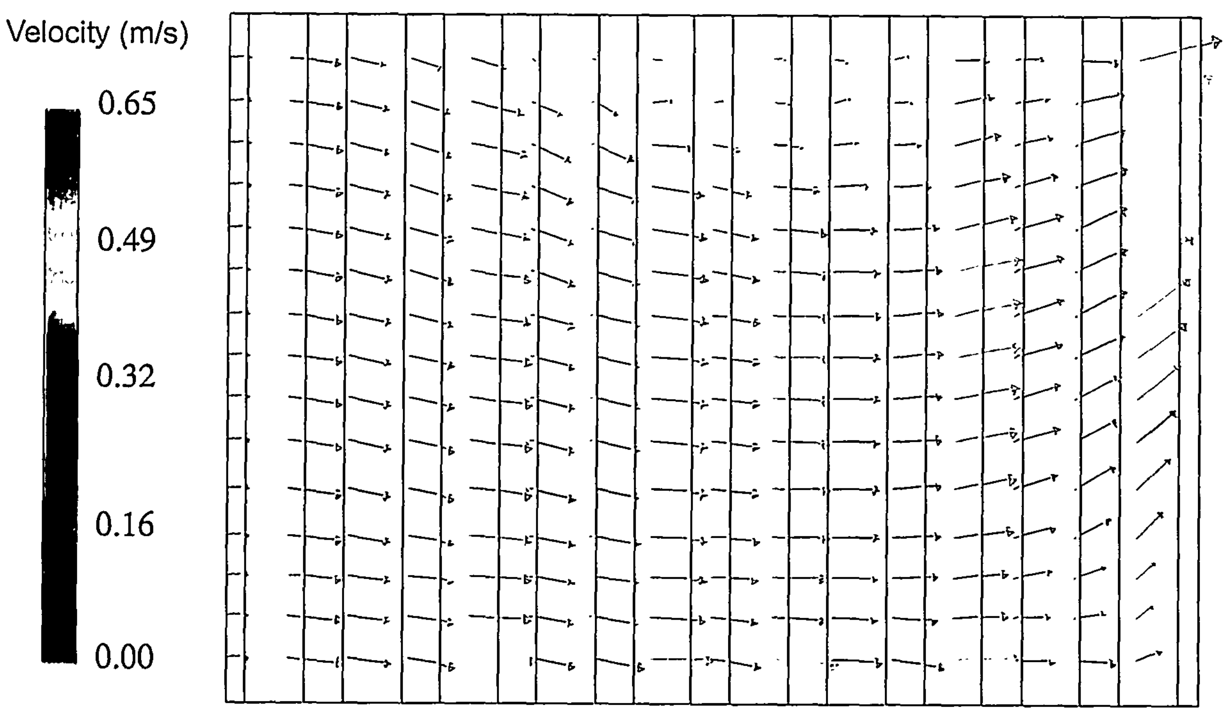


Figure 6. Temperature contour(a) and velocity vector(b) plots for porous media model with purely buoyant flow. Heat was distributed uniformly throughout block 2 only. The model carries a maximum temperature of 301.6 K and a maximum velocity of .48 m/s.



(a)



(b)

Figure 7. Temperature contour(a) and velocity vector(b) plots for the discrete ten tube model with, forced and buoyant flow. The model carries a maximum temperature of 302.3 K and a maximum velocity of .63 m/s.

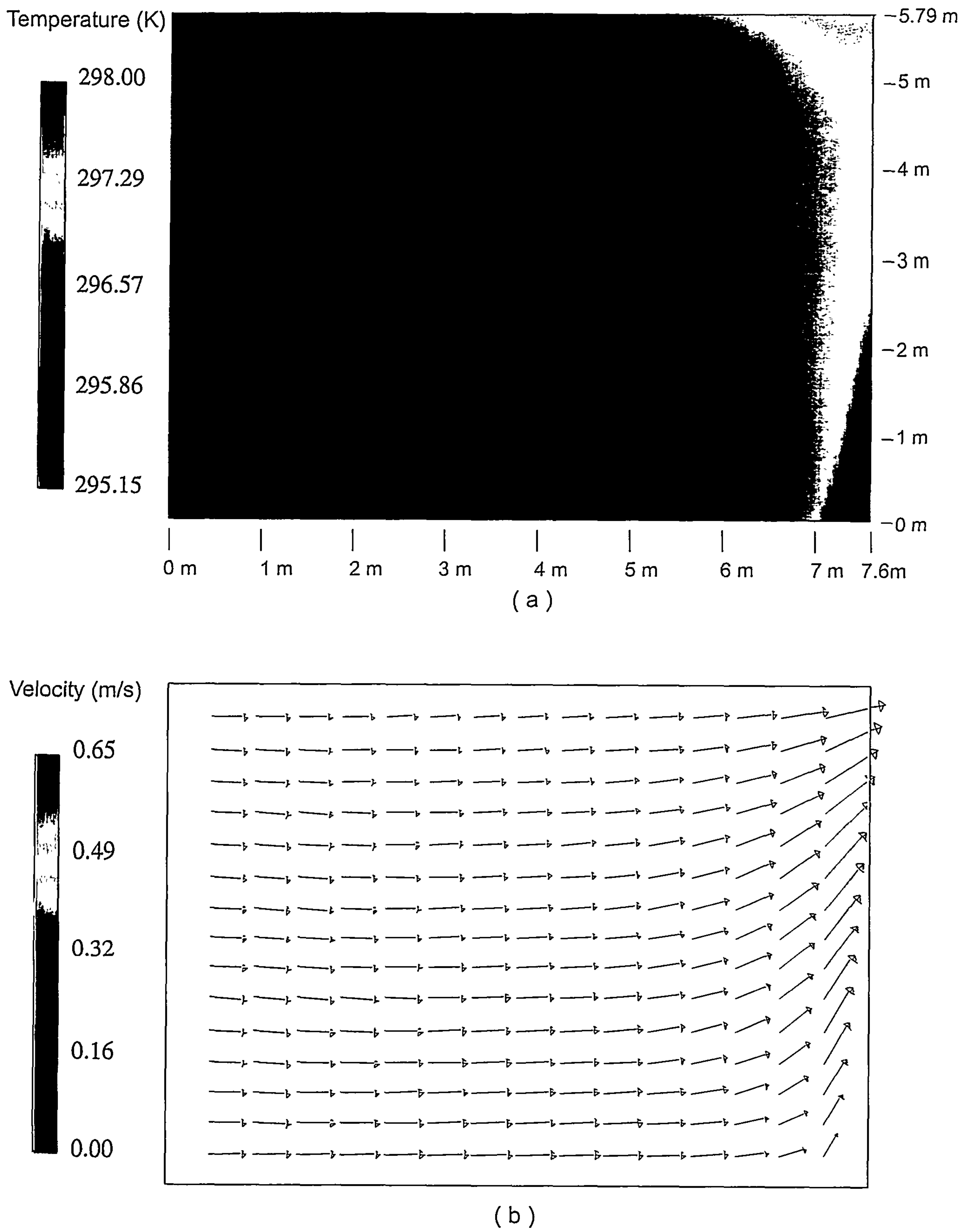


Figure 8. Temperature contour(a) and velocity vector(b) plots for the fully porous media model with forced and buoyant flow. The model carries a maximum temperature of 297.2 K and a maximum velocity of .465 m/s.

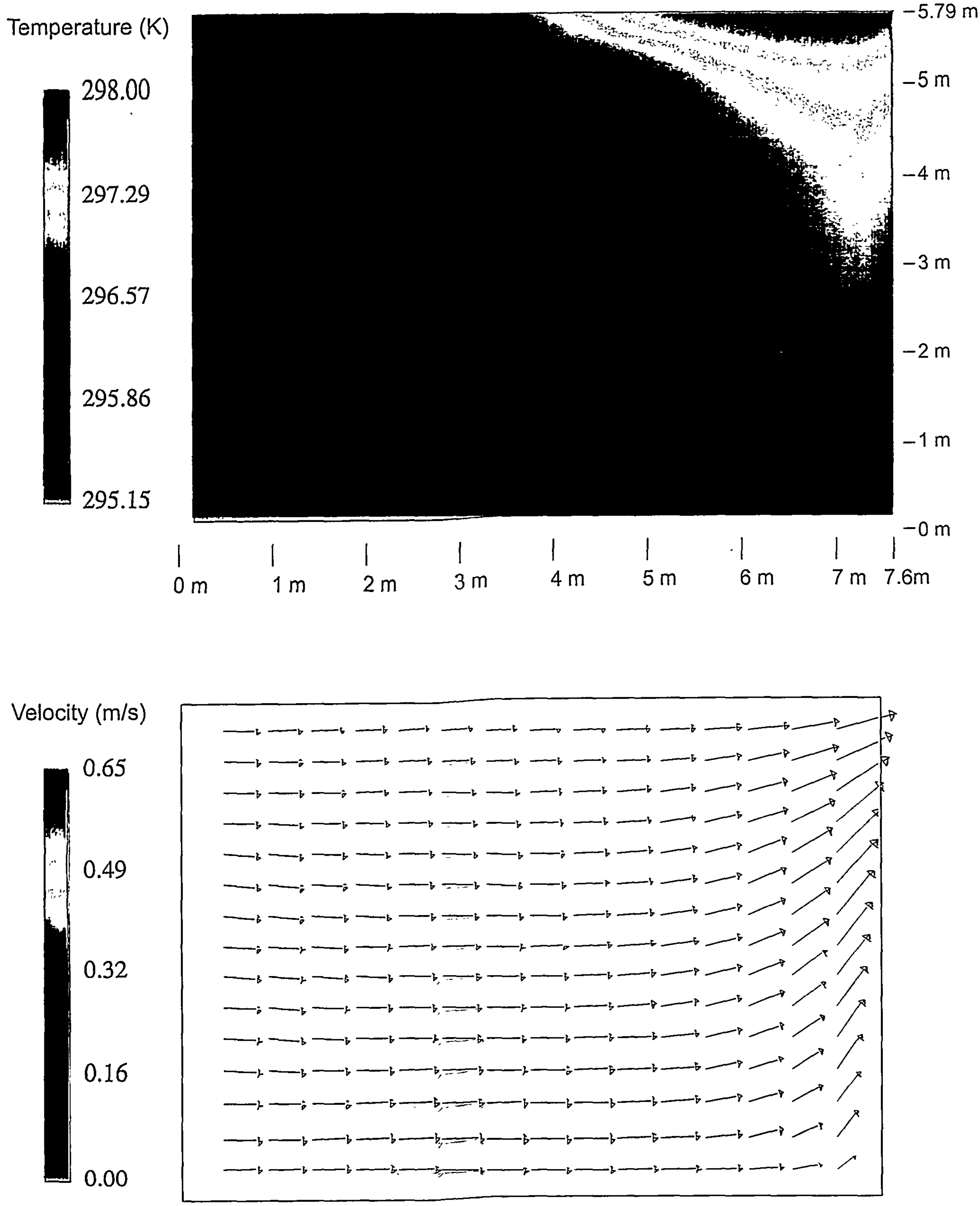


Figure 9.. Temperature contour(a) and velocity vector(b) plots for the porous media model with both forced and buoyant flow. Heat was distributed uniformly throughout block 2 only. The model carries a maximum temperature of 298.0 K and a maximum velocity of .49 m/s.

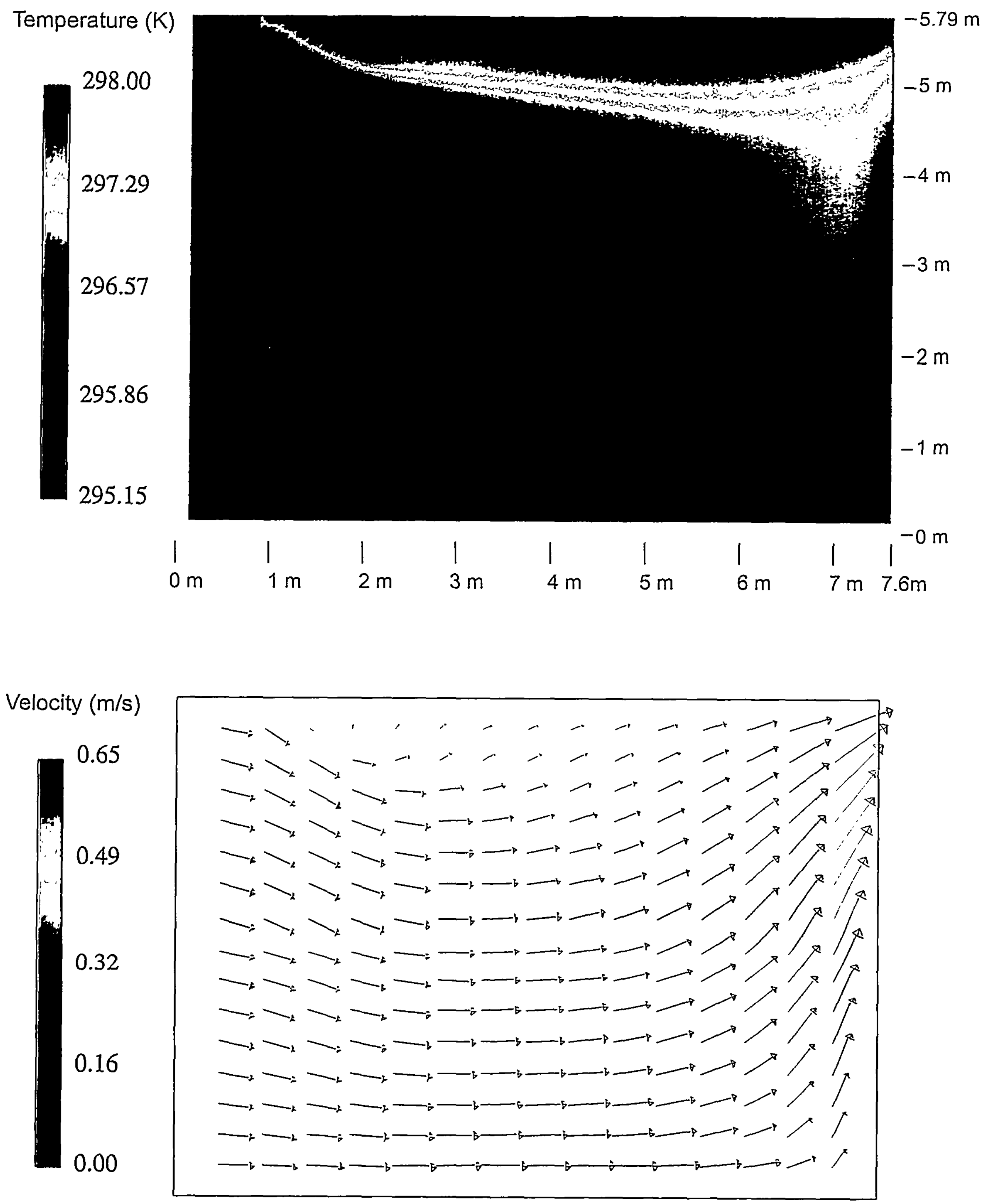


Figure 10 ..Temperature contour(a) and velocity vector(b) plots for the porous media model with both forced and buoyant flow. Heat and porous media were distributed through block 2 only. The model carries a maximum temperature of 301.5 K and a maximum velocity of .65 m/s.

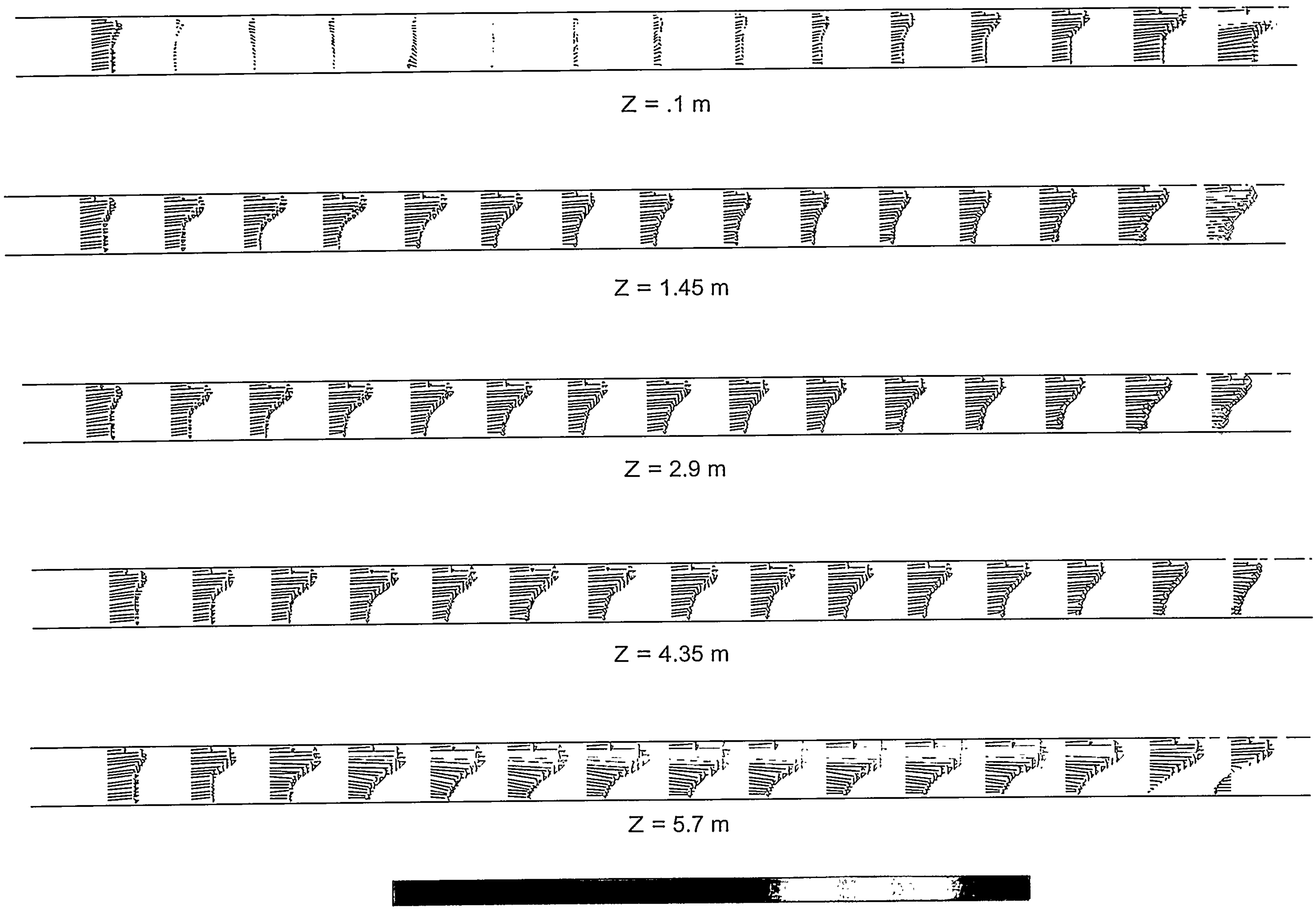


Figure 11 . Velocity Vector Plots of the model with porous media and heat uniformly distributed throughout block 2 only. .

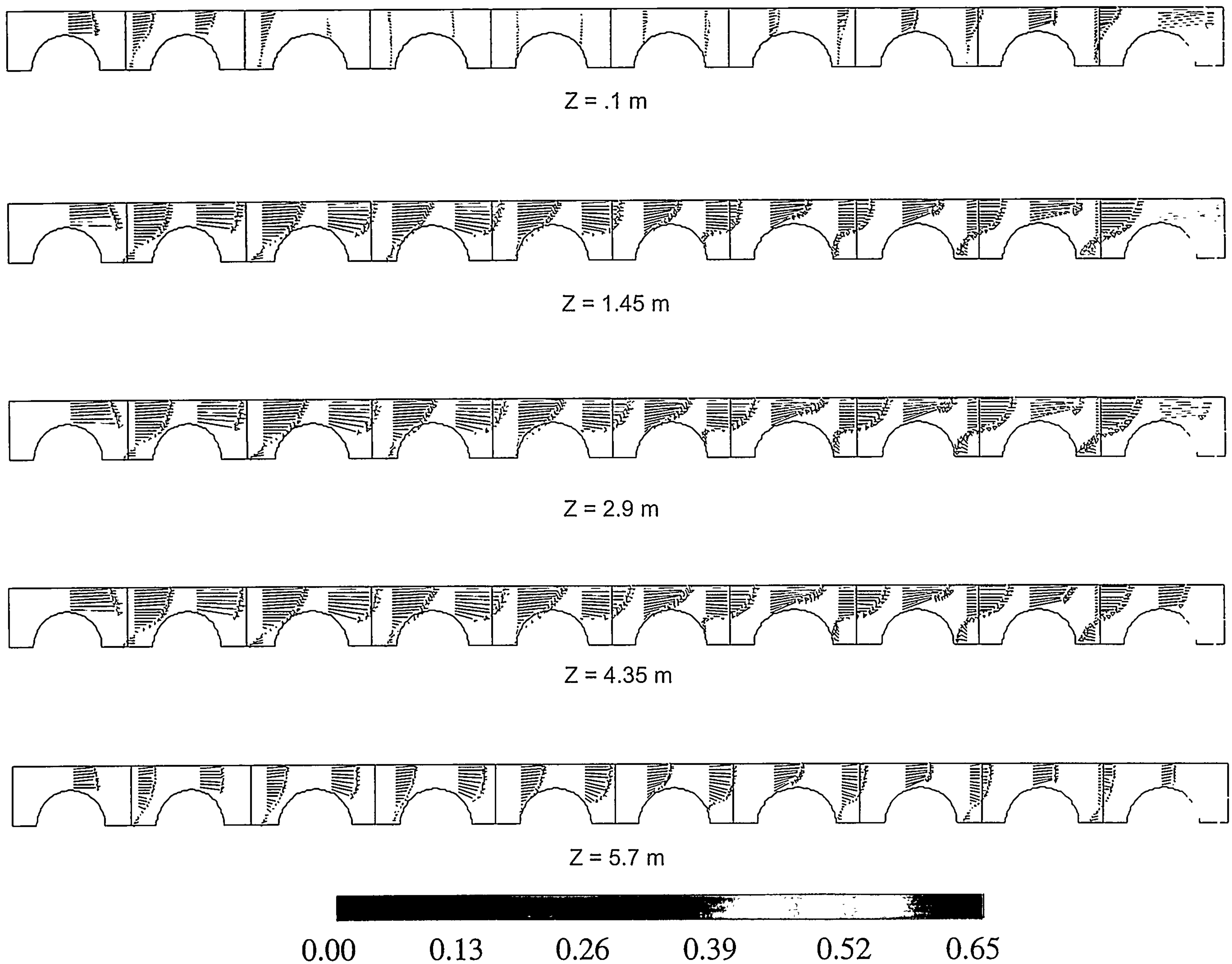


Figure 12. Velocity vector plots for the forced flow discrete ten tube model at various lanes in the Z axis.

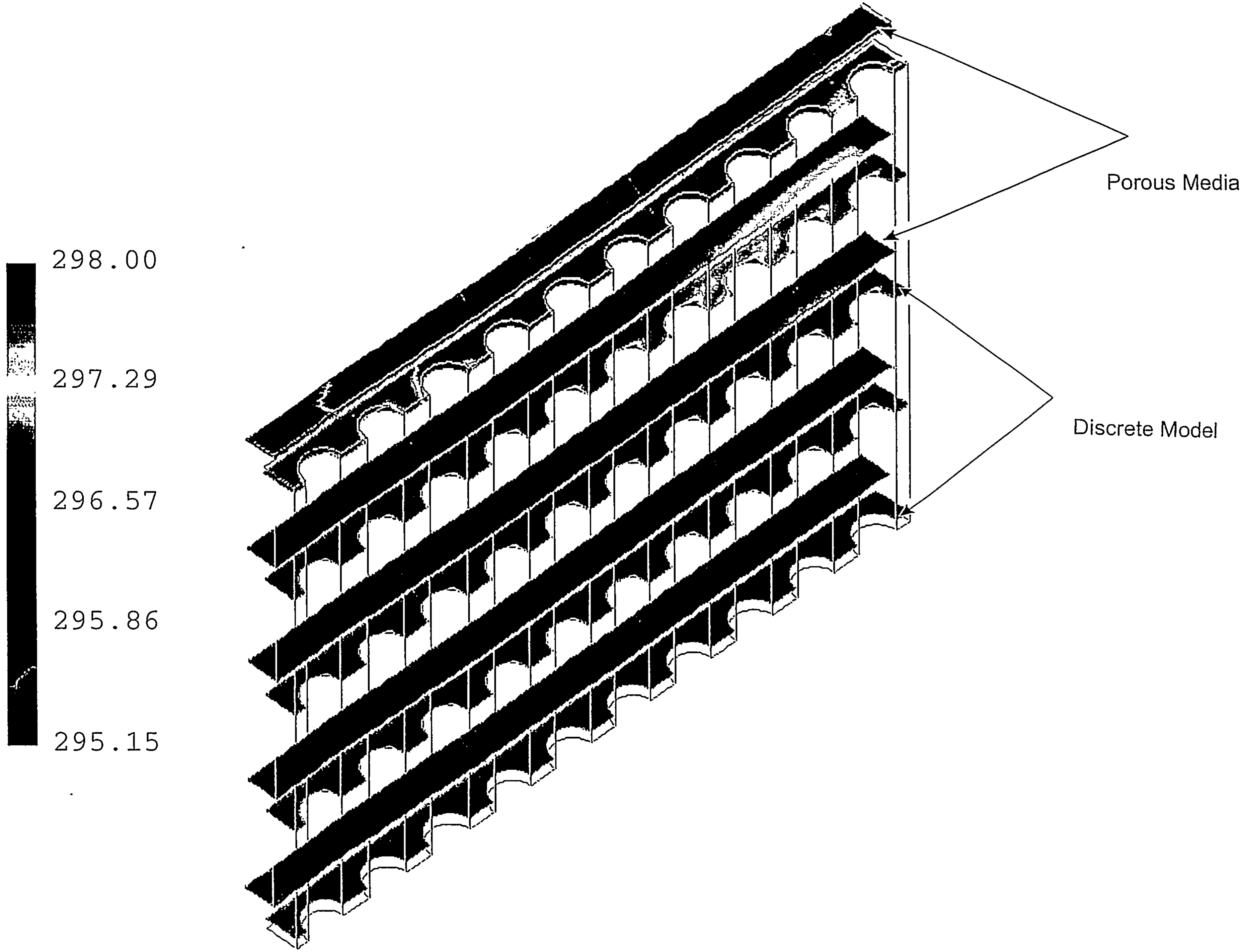


Figure 13. Discrete model with forced flow vs. Forced flow porous media model with porous media and heat distributed throughout block 2 only.