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The Effects of Black Liquor Sprays on Gas Phase Flows in a Recovery Boiler

by

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ABSTRACT

The complex gas flow patterns that occur in recovery furnaces have recently been the subject of several studies. Both physical and computational models have been used for these studies. For the most part these studies ignore the impact of the momentum of the black liquor spray on the furnace gas flow patterns. The purpose of the present study was to determine the magnitude of the effect of the sprays on the gas flow. This was done by computationally modeling the gas flows in a simplified recovery furnace geometry both with and without black liquor sprays. A simple analytical procedure was also used to estimate this effect. The results of this study show that the sprays do impact the flows but due to the large droplet size and the relative momentum of the sprays with respect to the gas flows this impact is modest.

INTRODUCTION

The combustion process occurring in recovery boiler furnaces has been the subject of intensive study in recent years. Direct observation and measurement of this combustion process have been frustrated by the hostile environment existing in the furnace. Analysis of the process has been limited due to the complicated multiple air port, multiple spray arrangement of these furnaces. This has led to the use and development of computer codes which solve the fundamental fluid mechanics and combustion equations (1-4) and to the use of isothermal physical models (5-7) to gain understanding of this complex process.

Much of the emphasis in development of improved practical air systems has been on understanding the air flow patterns in recovery furnaces. This understanding has been derived primarily from results obtained from isothermal physical models, though recently, computational fluid dynamics (CFD) models have confirmed and extended these results. However, most of these studies have been carried out by examining only the gas phase flows. The impact of the black liquor fuel spray on the gas flow pattern has not been accounted for. Neither gas-phase nor liquid-phase isothermal physical models lend themselves to inclusion of model black liquor sprays. Likewise, existing CFD codes are not well suited to analyze the full-coupled gas flow and combustion spray problem. The purpose of the present work has been to assess the magnitude of the impact of the spray on the gas flow pattern. If it could be shown that this impact is slight, then the use of single phase isothermal physical models, fixed-flow-field combustion calculations, and single phase CFD gas flow computations could be reliably used to examine the complete flow, mixing, and combustion patterns in recovery furnaces.

This paper is broken into two main sections. The first section contains a description of the physical interaction of the black liquor spray and the furnace gas flow along with a simple analysis of the magnitude of the interaction. The second section contains results from CFD computations for a simplified, isothermal recovery furnace both for the case with and without liquor sprays. Comparison of the flow pattern above the spray level is used to judge the magnitude of the spray-flow interactions. Conclusions are then drawn from the combined results of these two approaches.

ANALYSIS OF SPRAY-FLOW INTERACTION

A typical recovery boiler is a rectangular box approximately square in cross section with a height approximately three times the width. Air is injected into the furnace through multiple ports located on the vertical walls usually at three elevations. The black liquor sprays are also located on the vertical walls at an elevation above the two lower groups of air ports.

The air ports at each elevation are located on two opposing walls or on all four walls. The inwardly directed air jets are typically horizontal. When the air jets meet near the center of the furnace, they turn and form an upwardly directed gas flow channel which exits the furnace at the top. The black liquor sprays enter the furnace approximately horizontal (± 15°). As a result, the physical interaction between the spray and the gas flow is that of a horizontal spray encountering an upwardly flowing vertical gas channel.

The potential for interaction between the spray and the gas flow depends on the momentum transfer between the two. An initial estimate of the potential momentum transfer can be obtained by comparing the momentum of the two streams. The air jets are injected horizontally at very high velocities, typically between 40 m/s and 80 m/s. However, at the spray elevation, the gas flow has turned and is headed upward in a channel. The average gas flow velocity for the furnace cross section is typically about 3 m/s to 5 m/s. Because the gas flow is channeled, the peak upward velocity is about five times the average velocity. In the recirculation zone which surrounds the upward channel, the peak negative flow velocity is about equal to the average velocity. The upward gas velocity which would characterize the gas momentum will then be between the average gas velocity (~ 4 m/s) and about five times the average gas velocity (~ 20 m/s). For the present purpose, a value of 8 m/s will be used.

Black liquor sprays are introduced into the furnace through nozzles. The operating pressure and nozzle geometry result in spray velocities between 6 m/s and 12 m/s, making 8 m/s also a good estimate for the velocity characterizing black liquor sprays. To satisfy combustion air requirements, the air mass flow rate is typically three times the mass flow rate of wet black liquor. The momentum of each stream is equal to the product of mass flow and velocity. Using 8 m/s as the velocity which characterizes the momentum for each stream, the momentum ratio is just equal to the mass flow ratio. From this estimate the momentum of the black liquor spray is about one-third the momentum of the upward gas flow. Momentum of the gas stream is directed vertically and momentum of the black liquor spray is directed horizontally.

Based on the above simple estimate, the spray momentum is very significant with respect to the gas flow momentum. This would be particularly so with higher spray velocities and lower gas flow velocities. However, this comparison is between the two initial momentums. In fact, the interaction between the two phases involves momentum transfer resulting from the aerodynamic drag on the individual droplets. Not all of the spray momentum can be transferred to the gas. A somewhat better estimate for the interaction can be obtained by calculating the momentum lost by the droplets as they traverse a typical furnace cross section. For the purpose of this simple analytical analysis, gravity will be ignored.

The individual droplets start with an initial spray velocity and then decelerate due to the drag force. This force can be expressed as:

$$F_d = \frac{1}{2}\rho_g V^2 C_D A \qquad (1)$$

where

F_d = drag force, N

ρ_g = gas density, kg/m ^{3}

V = droplet velocity relative to gas, m/s

C_D = drag coefficient, unitless

A = droplet projected area, m ^{2}

The drag coefficient, C_D, is a function of the Reynolds number, Re, which is expressed as:

$$\mathrm{Re} = \frac{VD}{\nu_g} \qquad (2)$$

where

D = droplet diameter, m

ν_g = gas kinematic viscosity, m ^{2}/s

For black liquor sprays, 98% of the mass is contained in droplets with diameters between 0.5 mm and 6.0 mm. The minimum velocity (where momentum is negligibly low) is about 1 m/s, while the maximum velocity is about 15 m/s. Using a gas kinematic viscosity for air at 1150 °C (2100 °F) of 2 x 10^{-4} m ^{2}/s, the range of particle Reynolds number is approximately:

$$2.5 \le \mathrm{Re} \le 450 \qquad (3)$$

In this range of Re, the drag coefficient, C_D, can be estimated as:

$$C_D = \frac{17.1}{\mathrm{Re}^{0.6}} \quad \pm 15\% \tag{4}$$

The droplet momentum is:

$$M = mV \tag{5}$$

where

M = droplet momentum, kg m/s

m = droplet mass, kg

The change in momentum with respect to time can be expressed as:

$$\frac{dM}{dt} = -F_d \tag{6}$$

Substituting into (1) and assuming constant mass, the following differential equation for droplet velocity can be obtained:

$$m\frac{dV}{dt} = \tfrac{1}{2}\rho_g V^2 \frac{17.1}{\mathrm{Re}^{0.6}} A \tag{7}$$

By assuming droplets of constant size and density, the above equation can be solved to give the result:

$$\frac{M_L}{M_i} = (1 - 7.7\frac{\rho_g}{\rho_l}\frac{1}{\mathrm{Re}^{0.6}}\frac{L}{D})^{\frac{1}{0.6}} \tag{8}$$

where:

M_L = droplet momentum at L, kg m/s

i = indicates an initial value

ρ_l = density of the black liquor droplet, kg/m^3

L = maximum horizontal travel or furnace width, m

D = droplet diameter, m

The momentum ratio given in Equation (8) is shown plotted in Figure 1 as a function of droplet diameter for a wet black liquor specific gravity of 1.35, a gas temperature of 1150 °C (2100 °F), a maximum travel distance of 10 m, and three initial spray velocities. This figure shows that the larger droplets do not slow down as much as the smaller ones. The spray momentum is not efficiently transferred to the gas.

Figure 2 shows a typical black liquor spray size distribution with a mass median diameter of 2.6 mm. Using this distribution along with the momentum ratios for an initial velocity of 10 m/s results in an overall momentum transfer from the spray to the gas of 48%.

Based on estimates of the mass flows and velocities, the initial momentum of the black liquor spray is three times lower than the gas flow momentum. In addition, the large average droplet size for black liquor sprays reduces the transfer of momentum by more than 50%. As a result, the impact of the spray on gas flow would be expected to be fairly small. Finer, faster sprays would affect the gas flow more, while coarser, slower sprays would affect it less.

The above analysis is necessarily one-dimensional and uses a limited drag coefficient correlation. The following section makes use of a computational fluid dynamics (CFD) code to more fully and completely examine the spray and gas flow interaction.

CFD COMPUTATIONAL OF SPRAY-FLOW INTERACTION

A commercially available CFD code has been used to examine the interaction of a black liquor spray with a simplified recovery furnace gas flow. The code utilized was FLUENT v 3.02. It was run on an IBM RISC Workstation Model 6550.

Model Description

The essential features of the gas flow pattern in a recovery furnace are horizontal air injection from the vertical walls of the furnace box which results in a channeled upward flow. Such a flow can be generated by slot air injection ports on each wall located at a single elevation near the base. The black liquor spray can then be injected from one of the walls at a higher elevation so that the spray interacts with the upward flowing channel. For simplicity, the spray is assumed to be inert, nonevaporating, constant diameter droplets.

The geometry selected for these calculations was a rectangular box of square cross section, 10 m x 10 m x 30 m in dimension. The longest dimension is aligned vertically. The floor of the box is flat (i.e.,does not contain a char bed as would be found in most recovery furnaces). The entire top of the box is the outlet. A single horizontal air injection slot is located on each vertical wall at an elevation of 2 m. Each slot is 0.6 m high, and air is injected inward from each of the four slots at 64 m/s. The air density is specified as 0.24 kg/m^3 (corresponding to 1150°C or 2100°F). The calculated average upward gas velocity in the furnace was 4.1 m/s.

Three cases were considered: 1) gas flow without a black liquor spray, 2) gas flow with one liquor spray, and 3) gas flow with two liquor sprays located on opposite walls. The spray was taken as nonevaporating, non-reacting black liquor of 1.35 specific gravity. The spray fanned out in a horizontal sheet with edges ± 45° from the perpendicular centerline of the nozzle located in the center of the wall at an elevation of 6 m. The forward velocity was always 10 m/s. The total mass flow of black liquor was 35 kg/s corresponding to 35% of the gas mass flow. The droplet size distribution shown in Figure 2 was used with both spray cases.

The computational fluid dynamics program uses an iterative approach to establish the gas-droplet interaction. It first solves for the gas flow pattern without droplet injection. It then tracks the trajectories of the droplets as they move through and are influenced by the gas flow field. The results of the droplet trajectory calculations are cast in terms of mass, momentum, and energy exchange matrices which are then used as source-sink terms in a resolution of the gas flow pattern. These steps are repeated until a converged solution is reached.

For the present problem a 50,000 node grid structure was used along with the κ-ϵ model for turbulence for the gas phase solution. FLUENT uses a polynomial fit of the drag coefficient-Reynolds number correlation to give accurate values over the whole range of droplet sizes and velocities.

CFD Results

Contours of the vertical component of gas velocity are shown for a plane through the middle of the furnace in Figure 3 for the case with no sprays. Shown in Figure 4 are upward gas velocity contours at 10 m elevation and 25 m elevation. A generally central gas channel surrounded by recirculating zones is apparent in the contours at 10 m. Farther up the furnace, near the exit, at 25 m the channel has spread and dissipated considerably. This is a simple portrayal of the more complex channeled flows found in many recovery furnace model investigations.

Vertical velocity contours for the case with one spray are shown in Figure 5. Figure 6 contains similar contour plots for 10 m and 25 m elevations. In these two plan views, the nozzle is located on the lower side and is spraying upward. It can be seen in both figures that the near symmetry in the gas flow without the nozzle has been disrupted. The channel has been pushed upward, away from the nozzle. However, the general pattern of channeled flow surrounded by recirculation zones is still obvious.

Figures 7 and 8 show the results with two black liquor nozzles. The nozzles are located on the lower and upper sides of the plan views shown in Figure 8. The two opposed sprays do not move the flow channel from its generally central location, but do slightly change its shape. The nearly axisymmetric contours obtained without a spray are changed toward a flatter 2-dimensional channel across the furnace in the direction normal to the spray direction.

CONCLUSIONS

A simple analysis and computational study has been made of the impact of liquor sprays on recovery furnace gas flow patterns. Based both on a comparison of the momentum transfer from the spray to the gas and on the computational fluid dynamics results, several conclusions can be drawn:

1. Black liquor sprays in recovery furnaces can weakly affect the gas flow patterns.
2. This impact is relatively small due to the low momentum of the liquor spray and the moderate efficiency of momentum transfer.
3. Furnace gas flows are pushed and distorted by the liquor sprays, but the main features of channeled flow and recirculation zones are still apparent.

4. Ignoring the effects of the sprays in isothermal physical models is probably acceptable for many studies, though conclusions about detailed aspects of the flow and mixing may be in error. This could be important when comparing different air system configurations.

5. Using analysis with fixed gas flow fields will probably be adequate to determine the relative sensitivity of recovery performance to fuel, combustion, and spray parameters.

ACKNOWLEDGEMENTS

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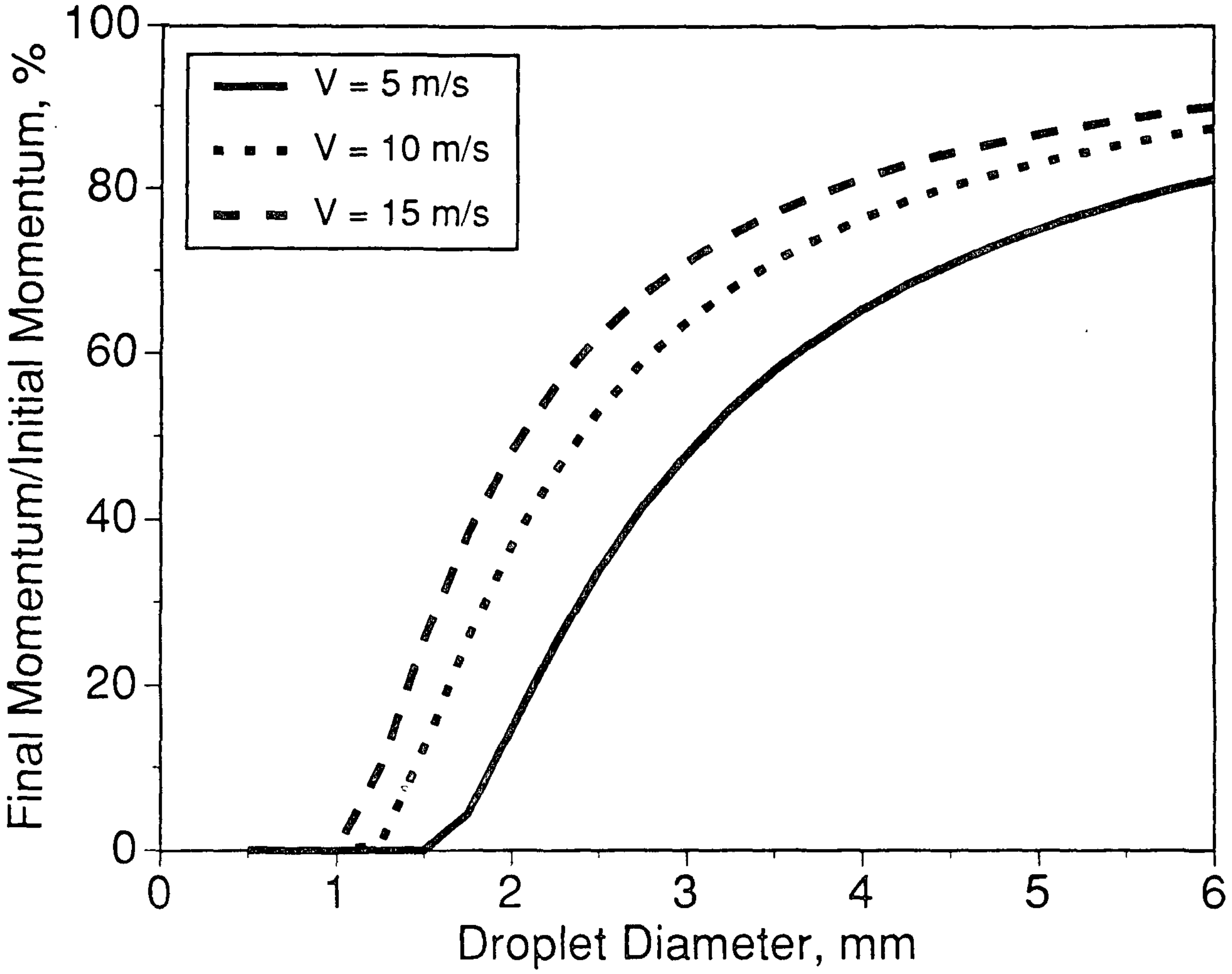

Figure 1. Momentum Ratio of Droplets as a Function of Droplet Diameter for a 10 m Horizontal Trajectory.

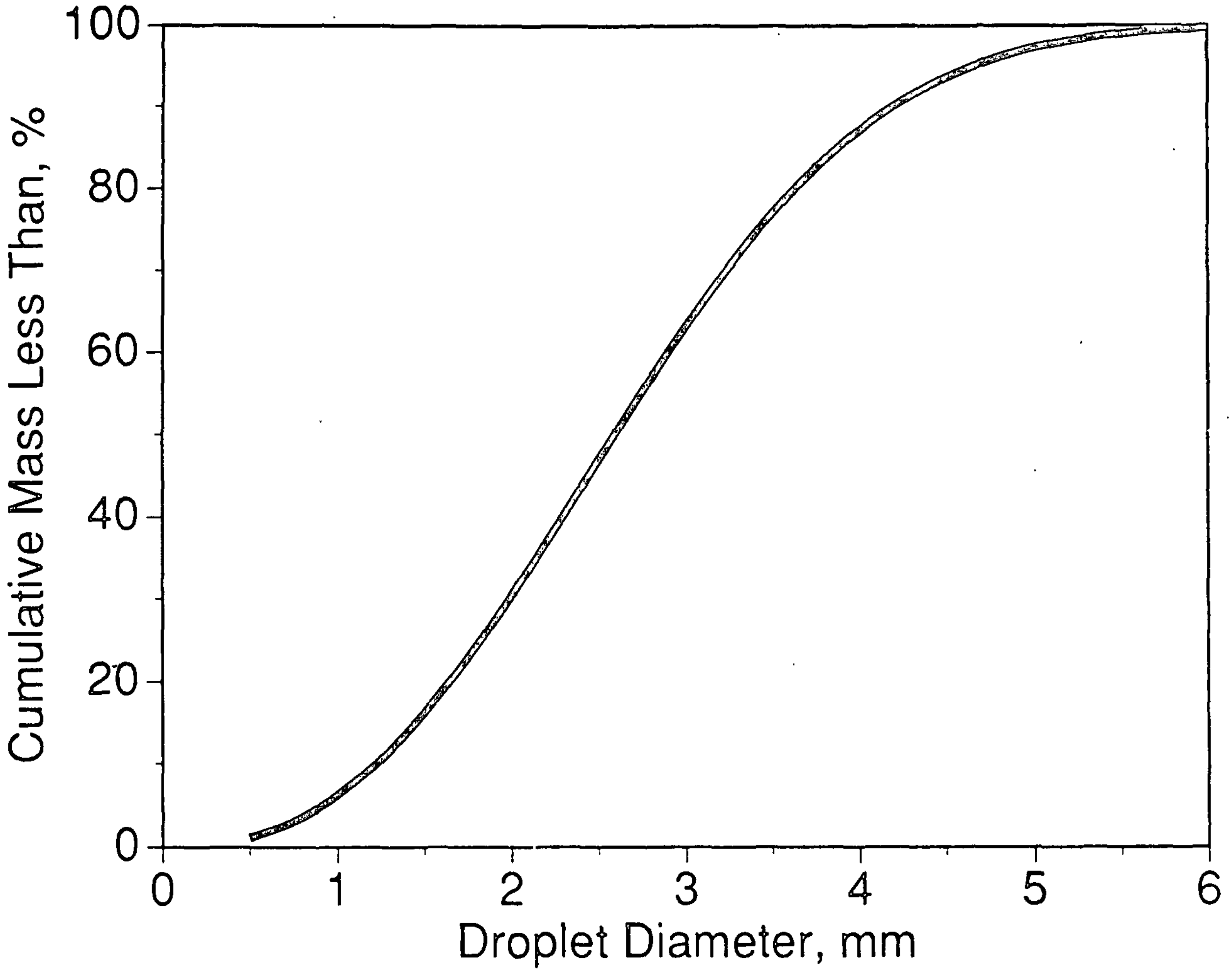

Figure 2. Typical Distribution of Droplet Diameters for Black Liquor Spray.

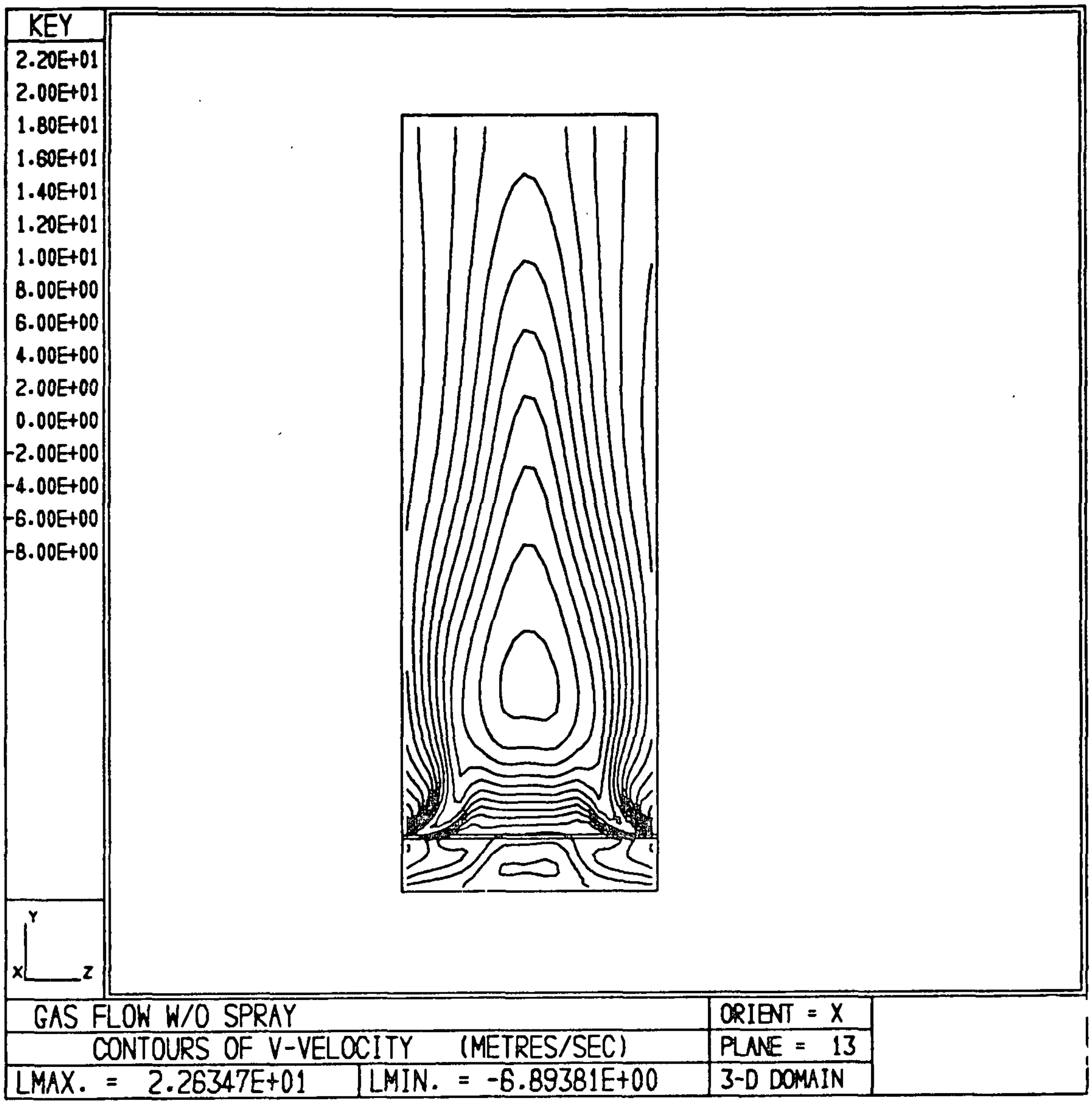

Figure 3. Contours of Vertical Velocity for a Plane Through the Center of the Furnace - No Sprays.

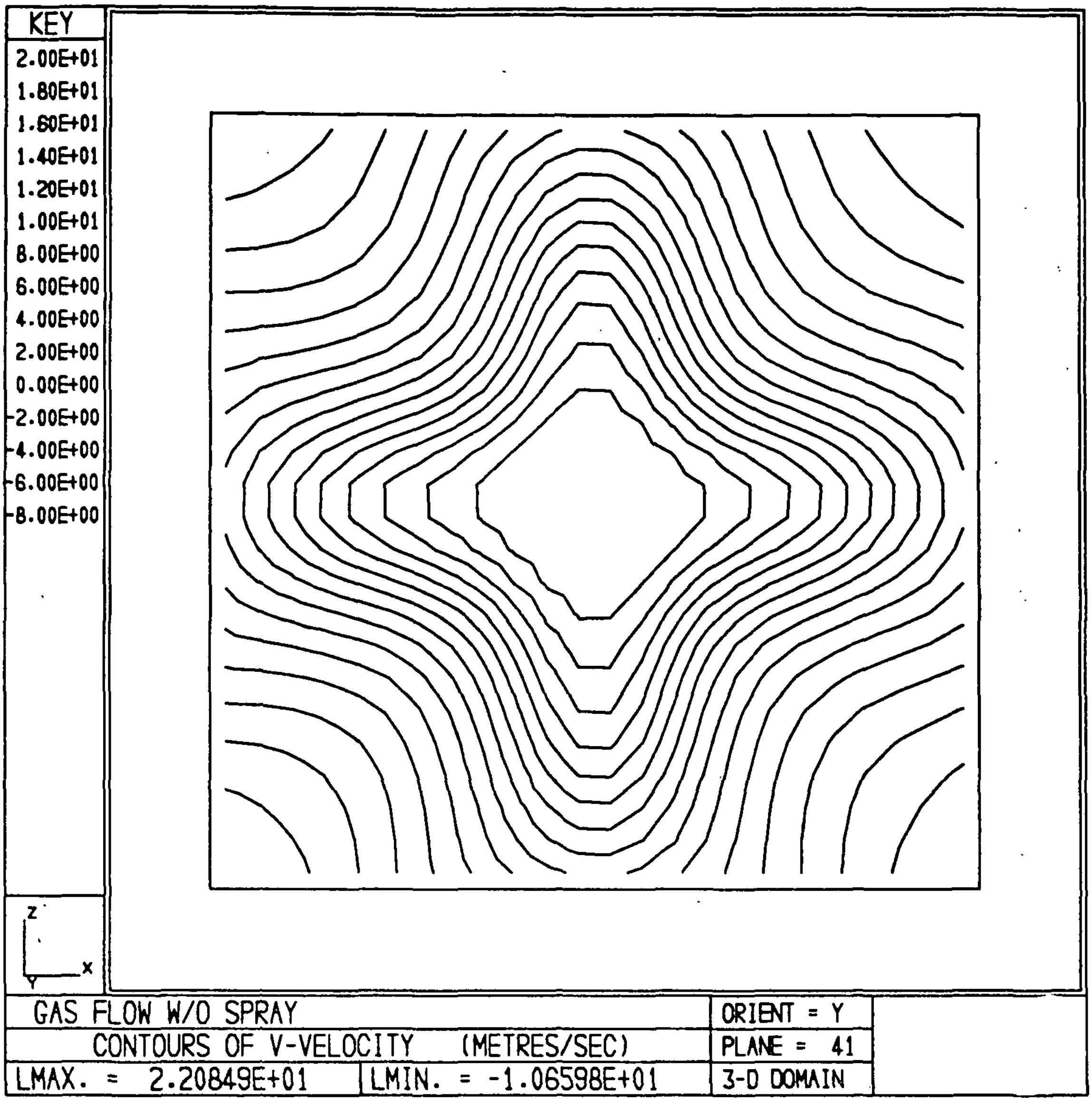

Figure 4.a. Contours of Gas Velocity at 10 m Elevation - No Spray.

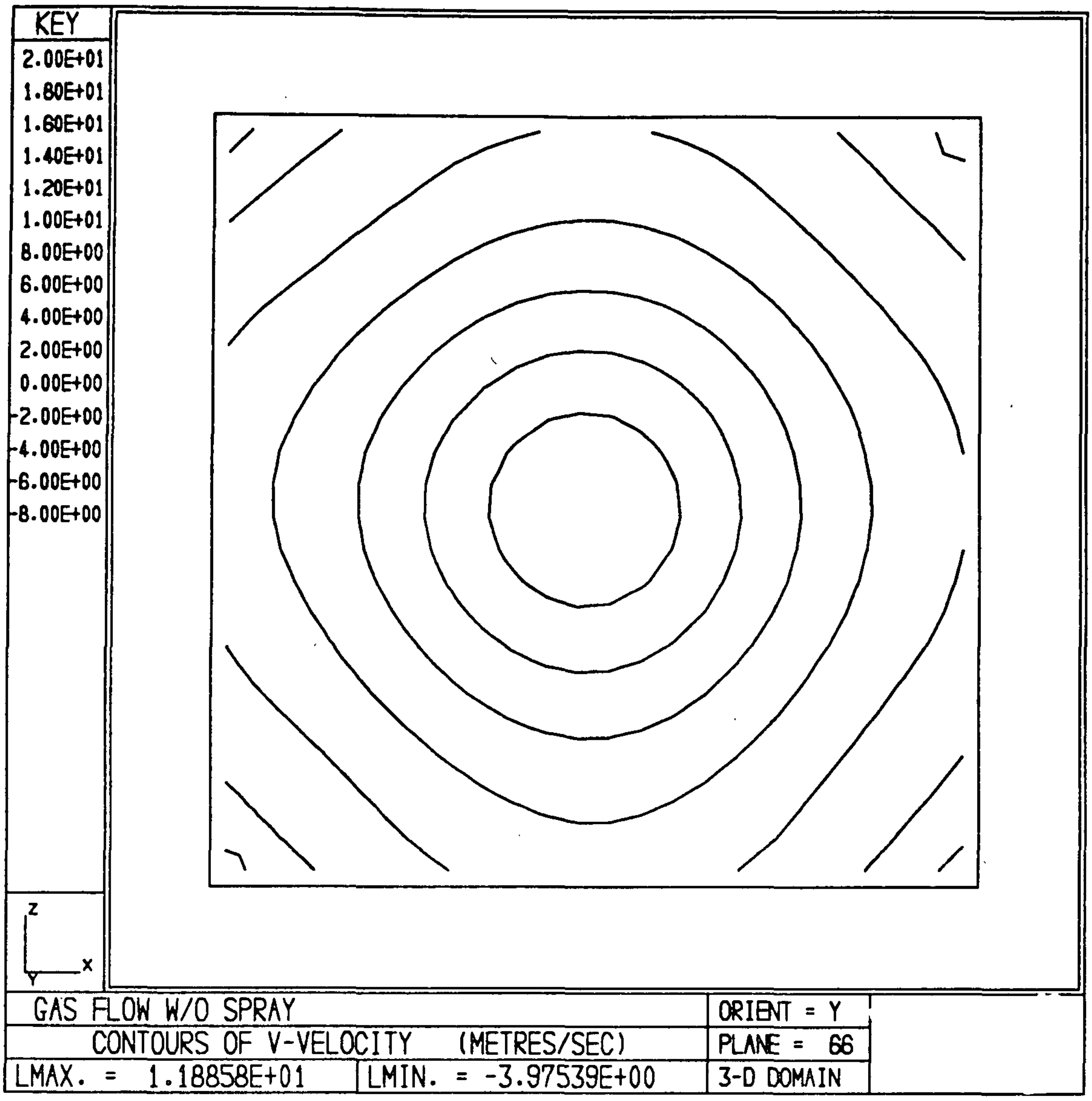

Figure 4.b. Contours of Gas Velocity at 25 m Elevation - No Spray.

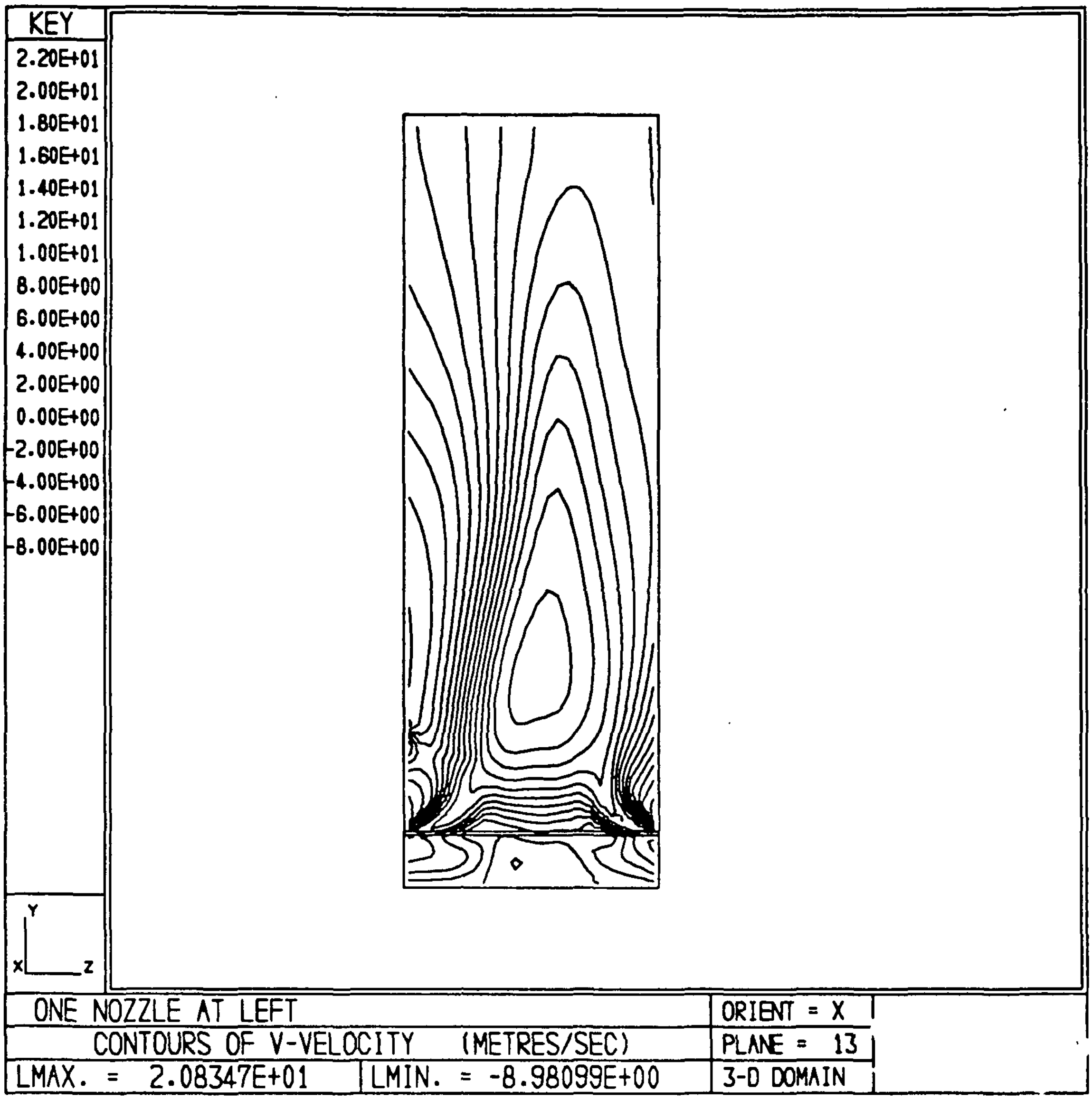

Figure 5. Contours of Vertical Velocity for a Plane Through the Center of the Furnace - One Spray, Left Wall.

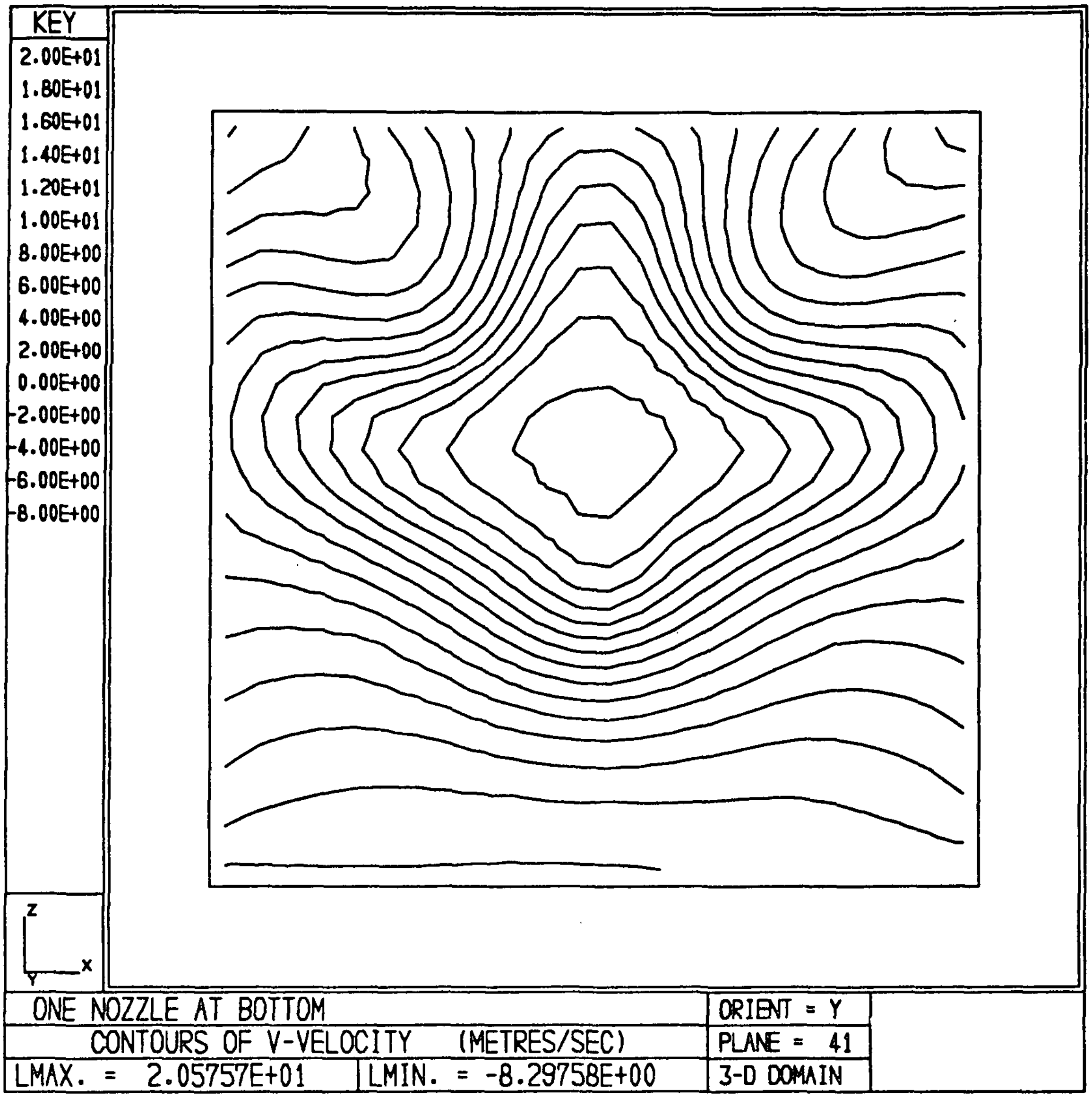

Figure 6.a. **Contours of Gas Velocity at 10 m Elevation - One Spray on Wall and is Lower Spraying Upward.**

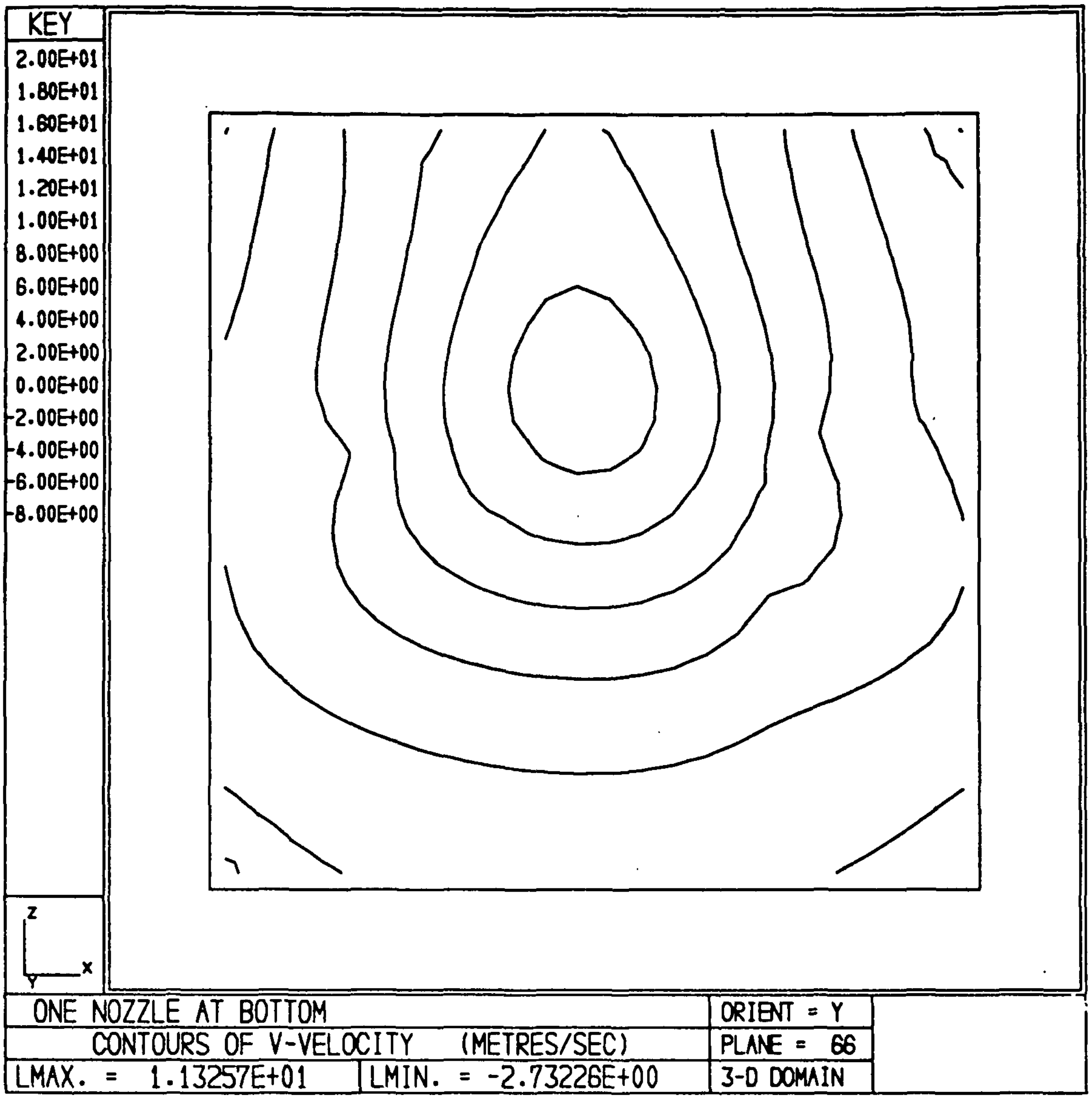

Figure 6.b. Contours of Gas Velocity at 25 m Elevation -One Spray on Wall and is Spraying Upward.

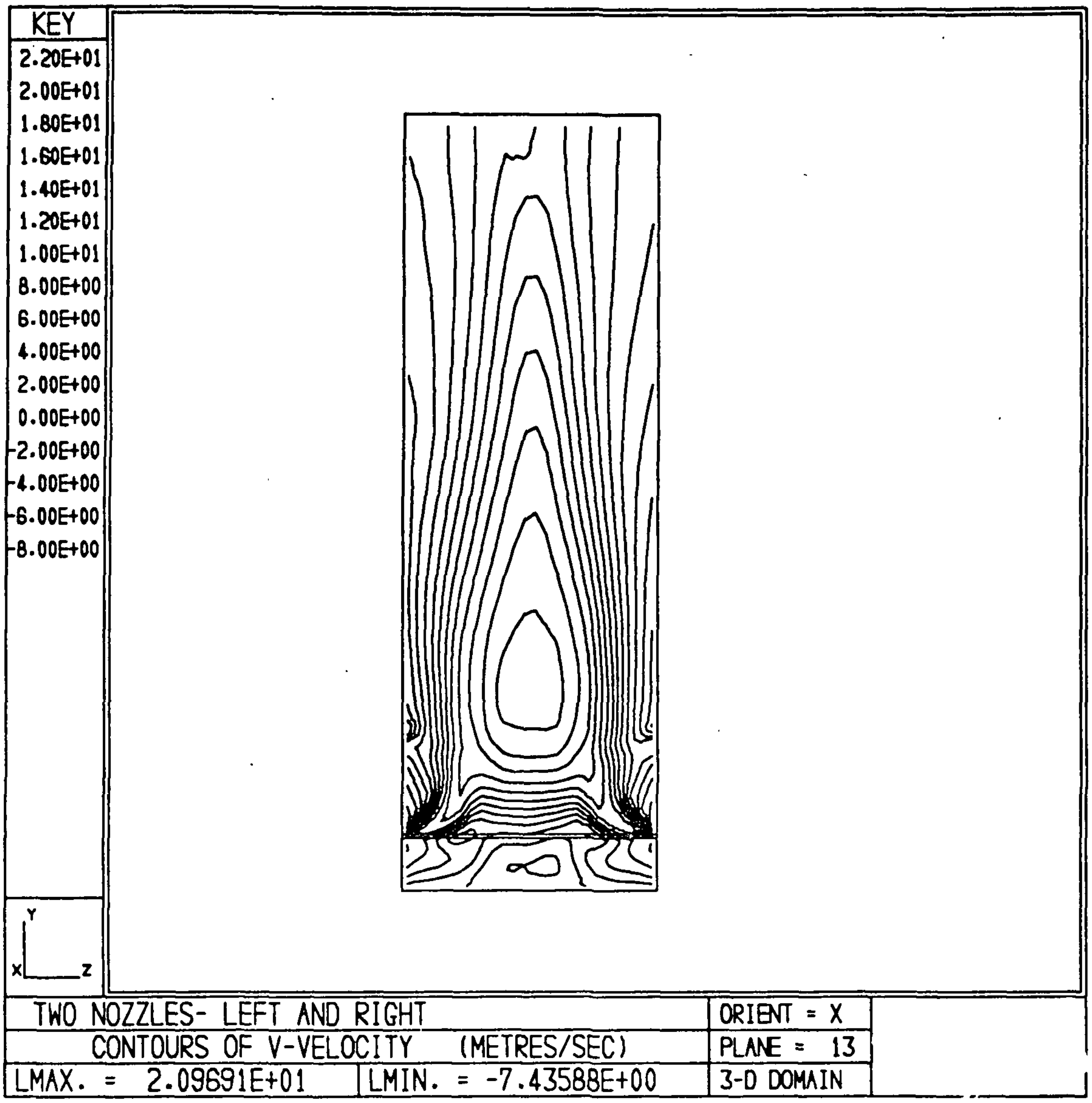

Figure 7. Contours of Vertical Velocity for a Plane Through the Center of the Furnace - Two Sprays.

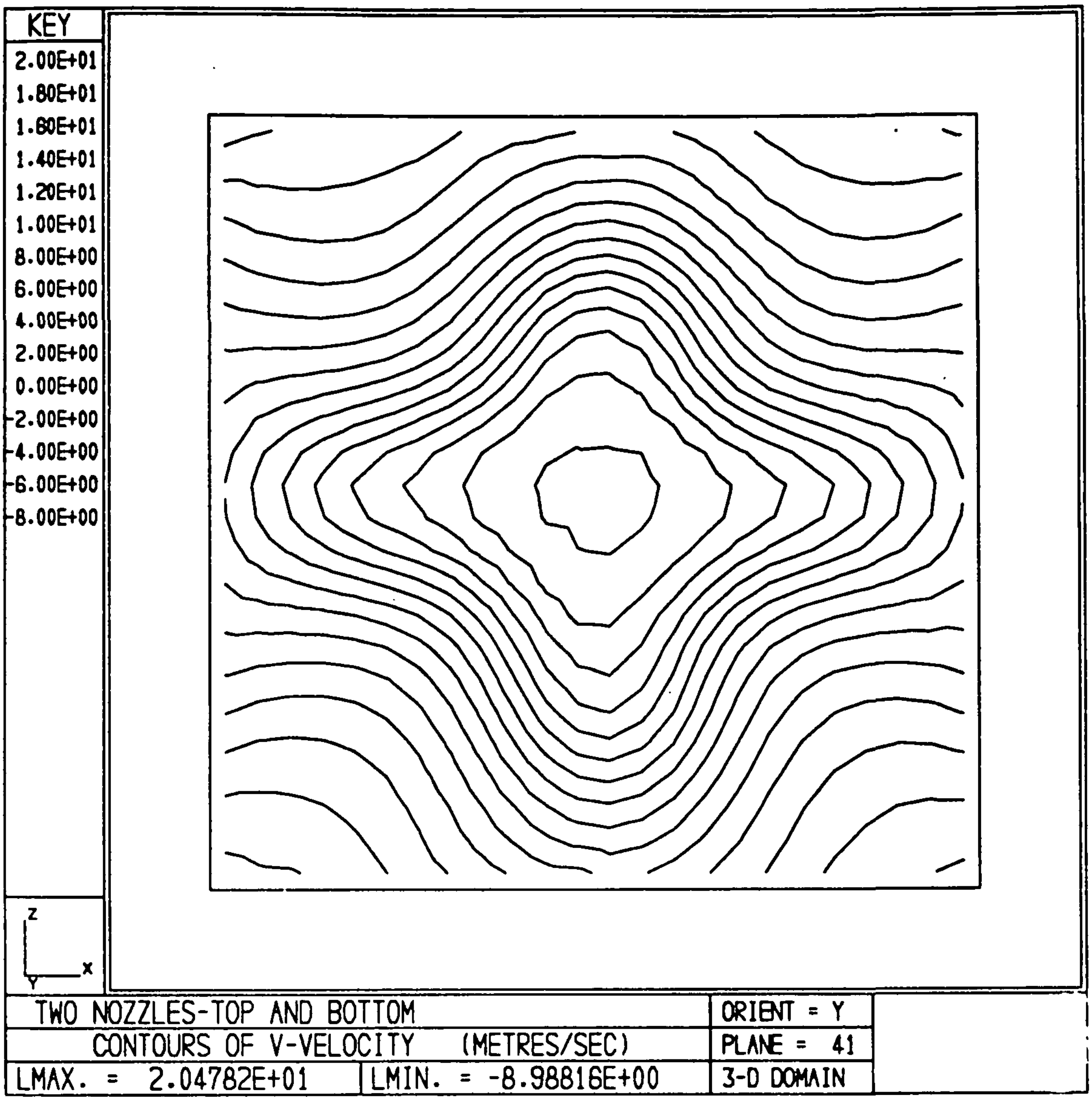

Figure 8.a. Contours of Gas Velocity at 10 m Elevation -Two Sprays on the upper and Lower Walls.

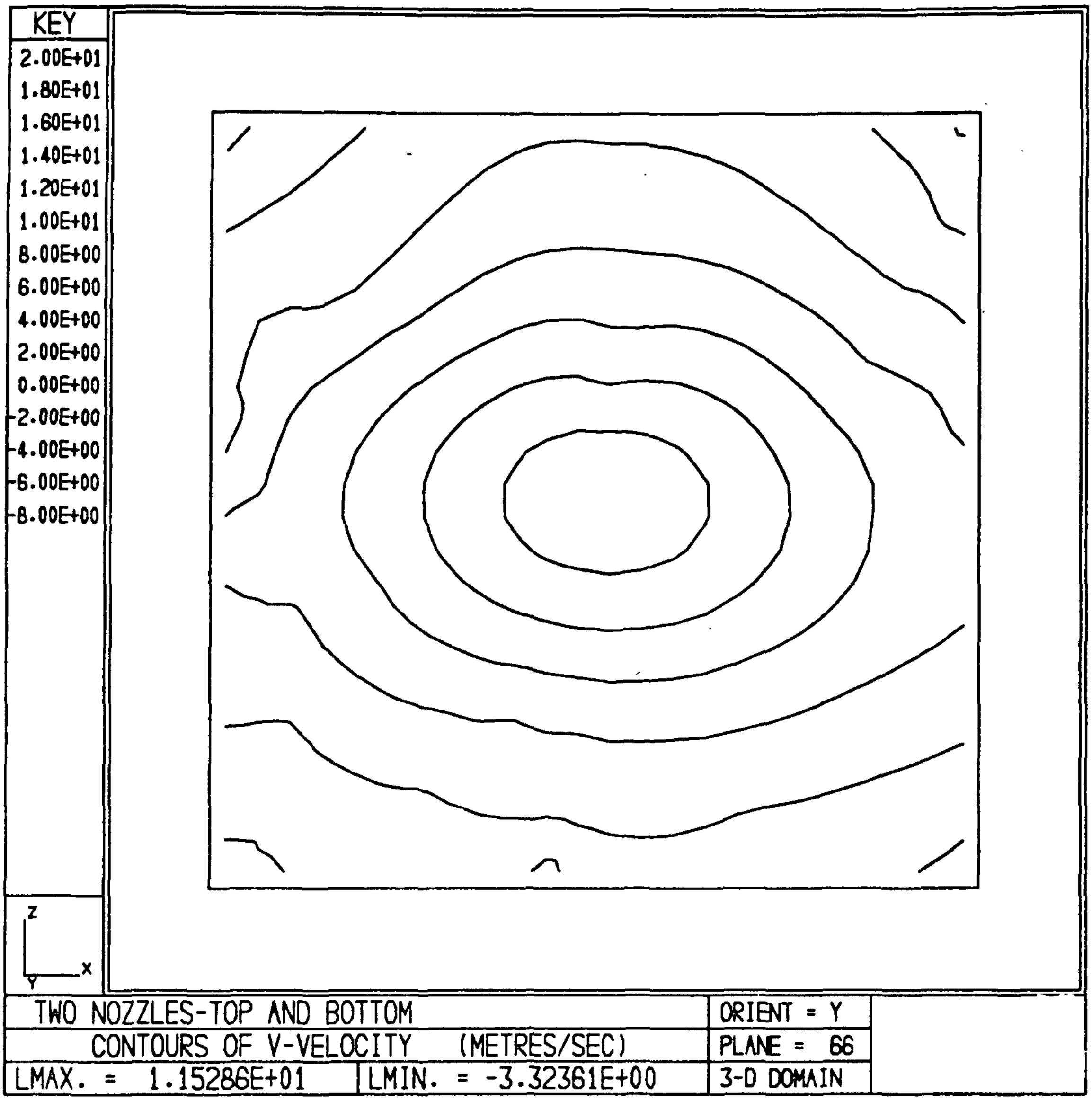

Figure 8.b. Contours of Gas Velocity at 25 m Elevation -Two Sprays on Upper and Lower Walls.