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ABSTRACT

A CFD study was conducted for the lower region of a recovery boiler furnace in order to study the flow patterns of air jets and their effects on the transport processes on a char bed surface. For a symmetric four-wall air system, interaction between air jets near a corner of the furnace results in a diagonal air stream that directs air flow toward the furnace center to form an upward central flow region. Air jets near the middle of a wall do not interact with perpendicular air jets directly, but they contribute to and are affected by the flow in the furnace center. For the moderately sized char bed shape examined in this study, distributions of shear stress and mass transfer coefficient indicate that char bed combustion is predominantly controlled by the primary air jets. The secondary air jets dominate the flow pattern of the main gas phase but make little direct contribution to the char bed combustion because they turn upward before reaching the char bed surface.

INTRODUCTION

Kraft black liquor recovery boilers have two main functions: combustion of the organic portion of black liquor to generate steam, and recovery of inorganic pulping chemicals. Black liquor is sprayed into the combustion zone of the boiler where it is mixed with air and undergoes four major combustion stages: evaporation, devolatilization, char burning, and inorganic reaction (1). Small particles may complete the combustion process while still in flight, whereas larger particles usually fall to the furnace floor to form a char bed and continue the combustion process there. An important inorganic reaction, sulfur reduction, takes place during black liquor combustion, and the char bed plays an important role in achieving high reduction efficiency (2).

Most of the air for char bed combustion is introduced through primary air ports located near the bottom of the boiler walls. Arrangements of the air jets can have a large influence on char bed shape since the air flow pattern determines the rate of oxygen transfer to the surface, which is often the rate-limiting step in char combustion. In turn, the shape of the char bed can affect the overall air flow pattern in the furnace by deflecting air jets that impinge on the char bed. Interaction between air jets and the char bed is a complicated process. Small-scale physical models and full-scale furnace observations are not likely to yield useful data in this area because the transport processes on the char bed surface are hard to measure or observe (3). Computational fluid dynamics (CFD) offers an attractive alternative for studying the air-jet/char-bed interaction (4-6), as well as flow and combustion in the gas phase (7-15) in recovery boilers.

A comprehensive study of a char bed requires sophisticated models to describe combustion of black liquor particles in flight, transport processes on the char bed surface, chemical reactions in the bed, and development of the shape of the char bed, in addition to a CFD solver. Before these models are developed, isothermal simulations of char bed phenomena can be conducted to increase our understanding of the complicated processes, facilitate the modeling work, and possibly provide suggestions for improving boiler operation and design.

In a previous study of char beds, slices of the lower furnace region have been simulated using symmetry boundary conditions (6). The slice models were useful in obtaining detailed flow patterns of isolated air jets, but they could not provide an overall picture of air jet interactions, especially interactions between perpendicular jets near the corners of a furnace. In this study, a simulation is carried out in a larger region involving one quarter of the lower furnace. Symmetry conditions are still used at the central planes of the furnace. Flow patterns of interacting air jets as well as interaction between air jets and char bed are investigated. The results offer an opportunity to verify the use of the slice models in studies of air-jet/char-bed interaction.

DESCRIPTION OF LOWER FURNACE MODEL

This paper reports on an isothermal CFD simulation that is carried out for the lower region of a recovery furnace. An isobaric boundary at the liquor gun level separates the computational region from the upper furnace. The furnace is assumed to be symmetric about two orthonormal, vertical planes; thus, only one quarter of the lower furnace region is described in the model. Figure 1 shows the geometry of the model. The horizontal cross section of the model is 5×5 m^2. The char bed has a smooth surface that is described by a curvilinear body-fitted-coordinate (BFC) grid (16). The air ports have been properly enlarged to compensate for the isothermal condition simulated here so that the volumetric flow rate in the furnace is comparable with combusting conditions. The primary air velocity is 50 m/s, and the secondary air velocity is 80 m/s. The distribution of air flow between the primary and secondary is 48% for the primary air ports and 52% for the secondary air ports. In a full-furnace simulation, additional air would typically be introduced at the tertiary level.

The CFD code used in this work is FLUENT version 4.11 (17) installed on an IBM RISC/600-550 computer. The computational region is represented by a BFC grid of nearly 150,000 cells ($68\times68\times32$). The number of cells is not enough to provide a completely gridindependent solution, especially for the primary air jets; however, the grid is sufficient for predicting major flow features properly. The κ-ε turbulence model is used in the simulation.

RESULTS AND DISCUSSION

Velocity Distribution

Flow patterns near the char bed surface and on two symmetry planes are shown in Figure 2. Due to the symmetric air port arrangement, the velocity distribution is symmetric about the vertical diagonal plane of the furnace. The primary air jets impinge on and flow along the char bed surface. Air jets near the corner of the walls penetrate shorter distances than those away from the corner due to interaction with air jets on the adjacent wall. The secondary air jets penetrate farther into the furnace. As they approach the furnace center, the secondary jets turn upward due to the action of a high pressure region above the center of the char bed, resulting in an upward high velocity flow in the center, and a low velocity recirculation region directly above the center of the char bed.

The primary air jets make a small contribution to the main gas phase flow pattern, but they dominate the flow near the char bed surface. The secondary jets dominate the flow pattern of the main gas phase with small contributions to the flow near the char bed surface.

Figure 3 shows a plan view of velocity vectors at the primary air port level. Perpendicular air jets near the corner of the furnace interact with each other, forming an air stream along the diagonal region. Air jets away from the diagonal region are less affected by the air jets from the adjacent wall. The situation is similar for the secondary air jets, as shown in Figure 4. The vectors in Figures 3 and 4 are not on flat horizontal planes, but rather on curved surfaces that follow the BFC grid lines.

In a previous study, slab and wedge-shaped models were used to study a slice of the char bed region (6). A slab model was believed to represent a symmetric two-wall air system, while a wedge model could represent a symmetric four-wall air system because the effect of air flow rate was included. Careful comparison between the results of the wedge model and the present model indicates that a secondary air jet in the middle of a four-wall air system is similar to that predicted by the wedge model, except that the jet in the wedge model turns upward slightly sooner. It appears that the jets at the symmetry planes in the present model correspond to a situation somewhere between those predicted by the slab and the wedge models. An important difference between the present quarter furnace model and the slice models is that the quarter furnace model can predict direct interaction between air jets from adjacent walls, but the slice models cannot. Therefore, the quarter furnace model is more realistic than the slice models.

Interaction between Air Jets and Char Bed

Air jets provide oxygen for char bed combustion. Flow patterns of the air jets determine the rate of oxygen transfer to the char bed. At the same time, air jets may entrain and redistribute char particles. Shear stress and mass transfer coefficients are major factors affecting these processes.

Figure 6 presents a plan view of the shear stress distribution on the char bed surface. The primary air jets produce a zone of large shear stress along the base of the char bed. This is expected since the primary jets are designed to remove char quickly in this area by combustion and particle entrainment. In comparison, the secondary jets make little contribution to the shear stress distribution, mainly because the secondary jets are far from the char bed and the jets turn upward before impinging on the char bed. Consequently, the top of the char bed is covered by a relatively stagnant atmosphere. Combustion may be slow in this region allowing the char bed to grow above the secondary level in some cases.

Figure 7 shows a plan view of mass transfer coefficient distribution, which is calculated from values of local shear stress and velocity using the following relationship derived from the Chilton-Colburn analogy (19):

$$k = \frac{\tau_w}{\rho u_p} Sc^{-2/3} \tag{1}$$

where k is the mass transfer coefficient; τ_w is the shear stress; Sc is the Schmidt number of the gas (≈ 0.7); and ρ is the gas density. The pattern of the mass transfer coefficient profile shows that the primary air jets would play an important role in combustion.

The above predictions of shear stress and mass transfer coefficient are only qualitative because the effects of temperature and chemical reactions are not considered. Surface roughness also needs to be carefully specified in more realistic simulations since the calculations of the transport processes are very sensitive to the surface roughness.

CONCLUSIONS

The air flow pattern in the lower furnace region and the transport processes on the char bed surface have been studied using a CFD char bed model. For a symmetric four-wall air system, interaction between perpendicular air jets results in a diagonal air flow toward the furnace center, forming a high velocity central core. Air jets near the middle of a wall do not interact with perpendicular air jets directly; however, they contribute to and are affected by the central core.

Primary air jets play a major role in char bed combustion. By impinging on the char bed surface, primary air jets provide both fresh air and rapid mass transfer to the char bed. In this study, the secondary air has a smaller impact on the char bed, partly because the central core prevents the jets from impinging on the bed surface.

ACKNOWLEDGMENT

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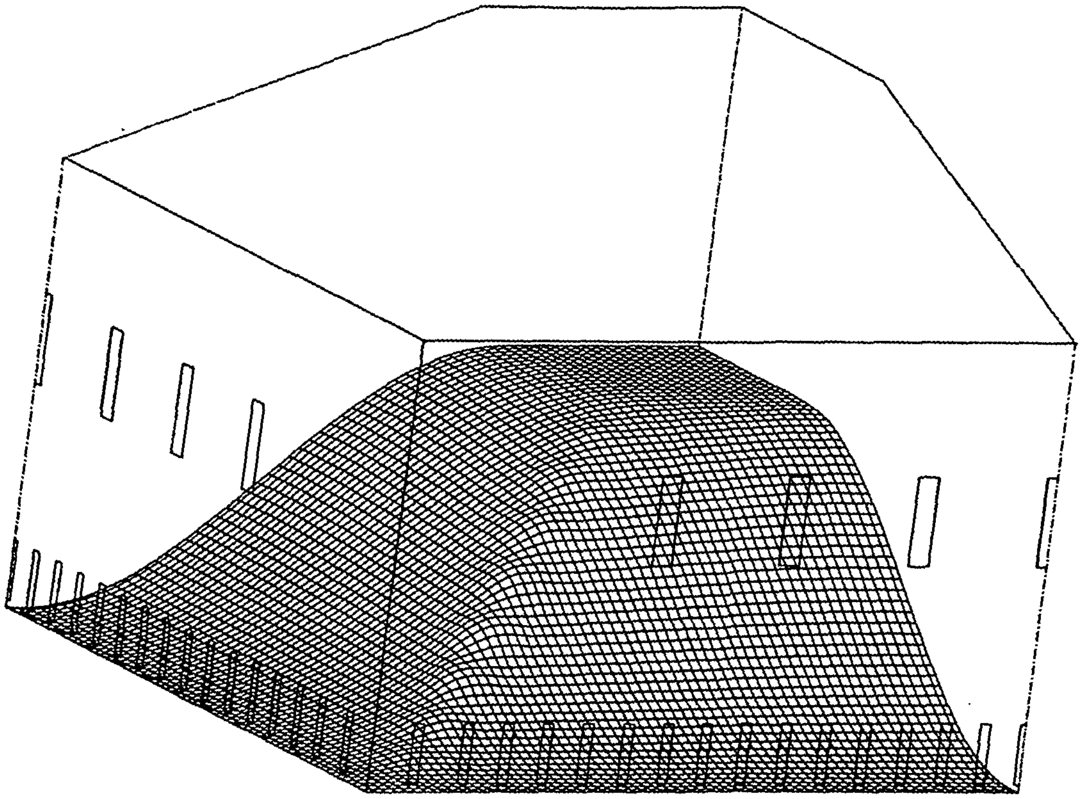

Figure 1. Geometry of the CFD char bed model.

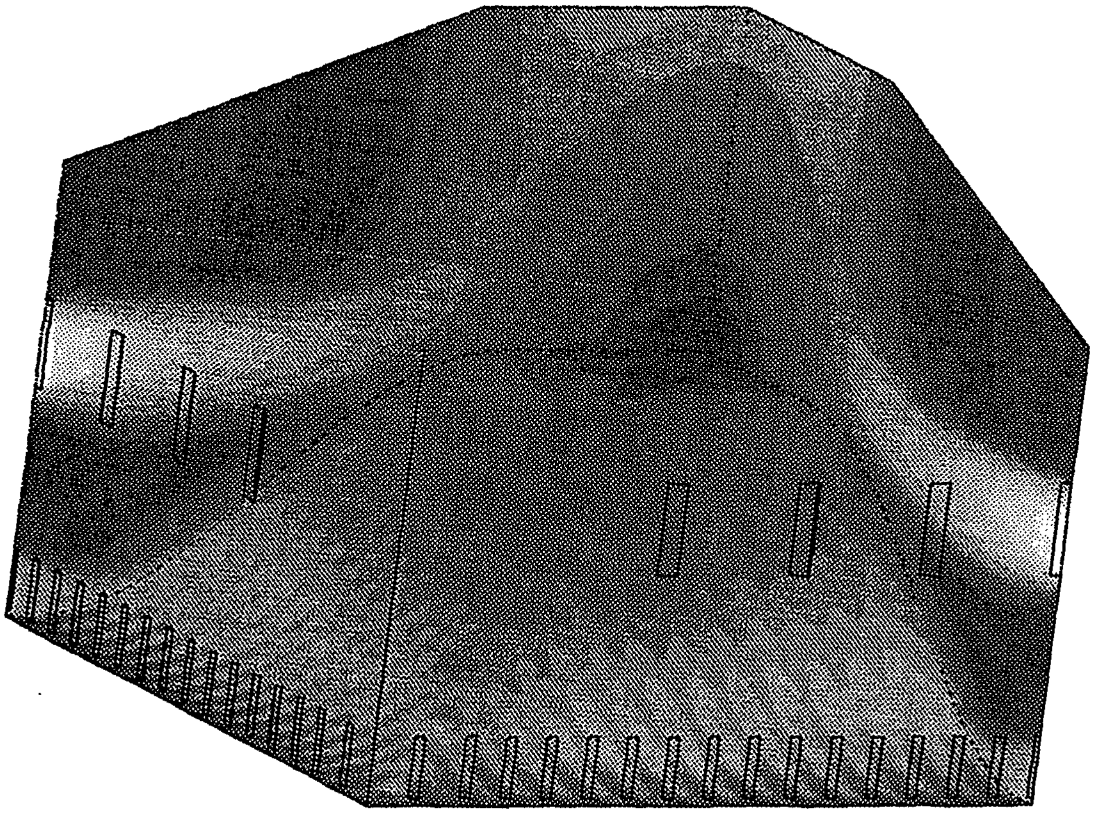

Figure 2. Velocity distributions on the symmetry planes and near the char bed surface.
Gray scale = 0 - 80 m/s (dark - bright).

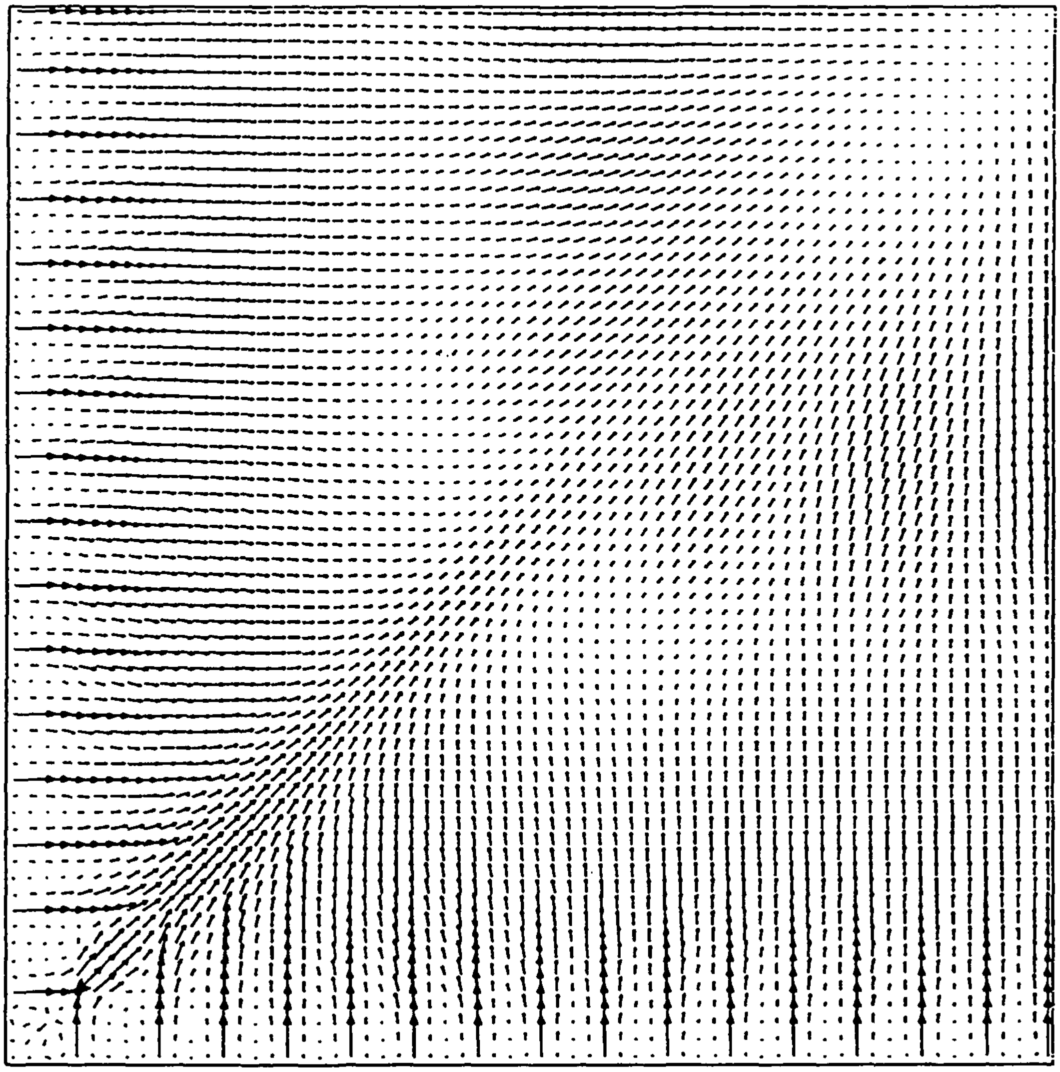

Figure 3. Velocity vectors at the primary air level.

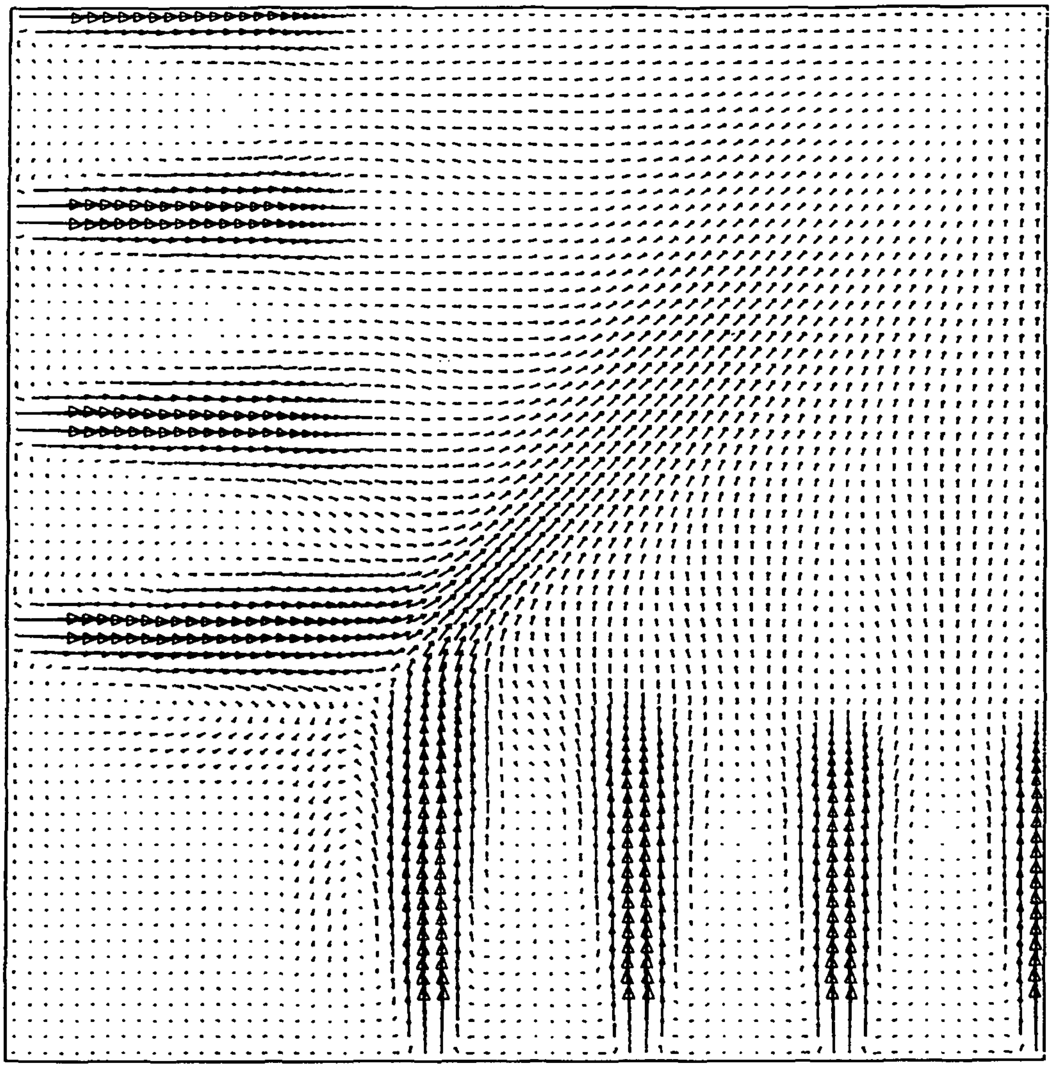

Figure 4. Velocity vectors at the secondary air level.

Figure 5. Vertical velocity distribution at the upper boundary.
Gray scale = -15 - 30 m/s (dark - bright).

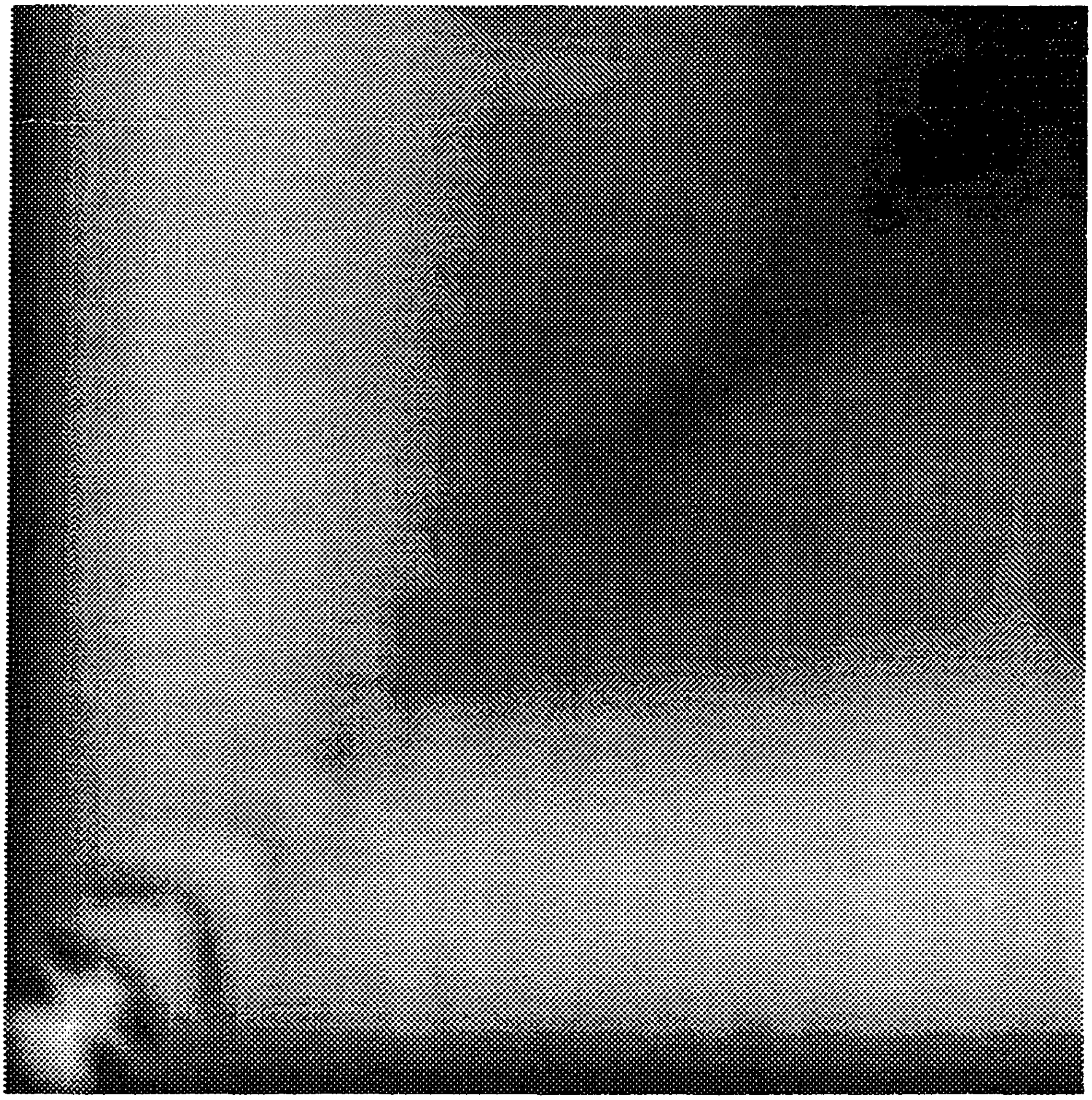

Figure 6. Shear stress distribution on the char bed surface.
Gray scale = 0 - 1.19 Pa (dark - bright).

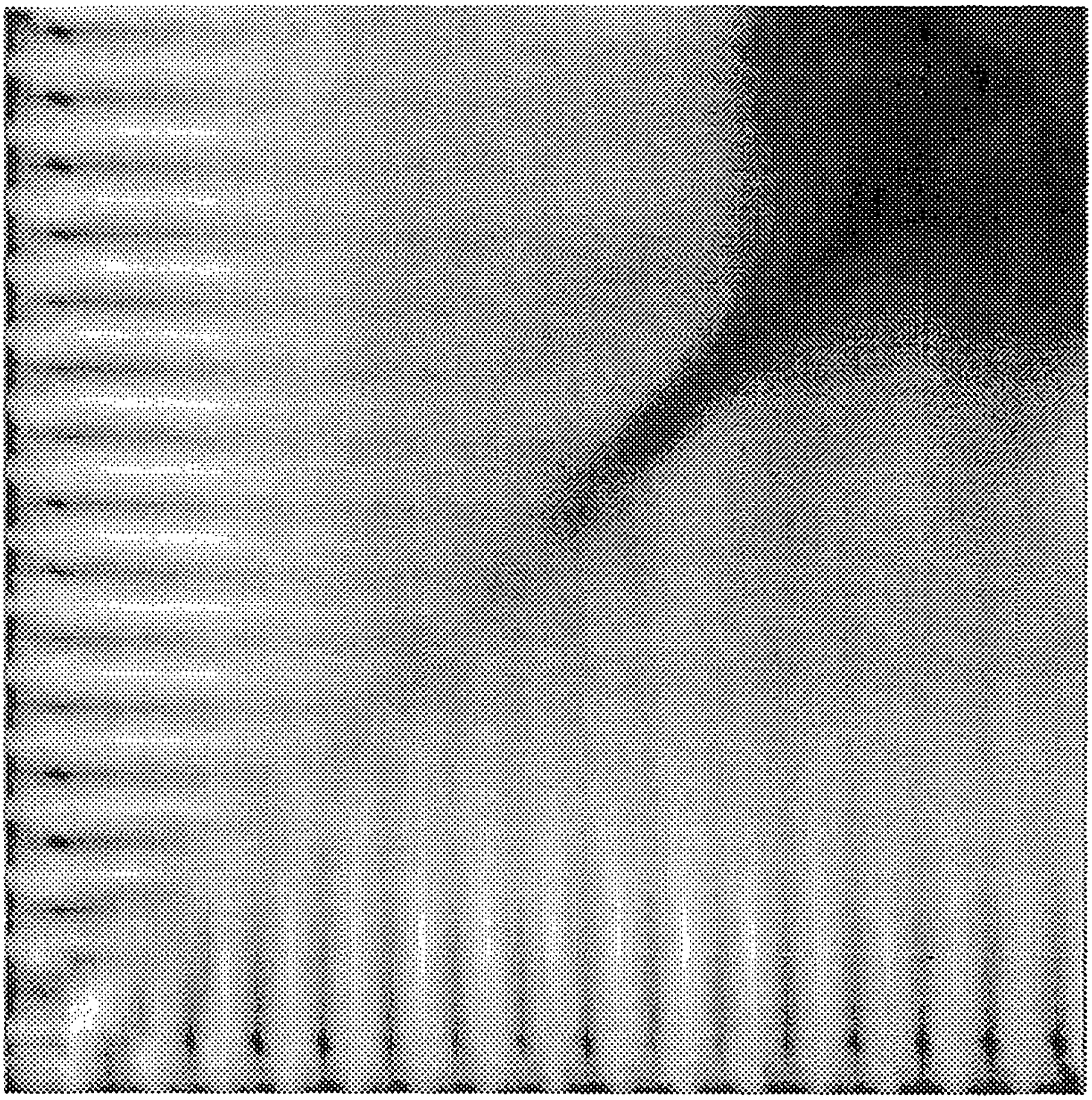

Figure 7. Distribution of mass transfer coefficient on the char bed surface. Gray scale = 0.01 - 0.16 m/s (dark - bright).