非均勻穀床之風場分佈

Air Flow Distribution in Nonuniform Grain Beds

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摘要

爲分析非均勻穀床之風場分佈而發展的有限差分數值方法已成功地建立，此數值模式可應用於均質與非均質的系統。電腦模擬指出穀床的非均質性與非均勻性是影響風場均勻分佈的重要原因，同時穀床物理狀況的調整可以改進風場的不良分佈。

關鍵詞：非均勻、模擬、穀物、風場

Abstract

A finite difference numerical scheme for air flow distribution in nonuniform grain beds has been successfully developed. The scheme can be applied to both homogeneous and heterogeneous systems. The simulations show that the heterogeneity and nonuniformity of grain beds play important roles in the uniform distribution of air flow. The results also show that the maldistribution of air flow in the grain bed can be improved if physical conditions of the bed are adjusted.

Keywords: NONUNIFORM, SIMULATION, GRAIN, AIR FLOW

INTRODUCTION

The understanding of air flow distribution is of practical importance in grain storage and drying operations. The heterogeneous grain beds which consist of grains and other materials such as fines and/or foreign materials exhibit different characteristics of air flow patterns from those of homogeneous beds. Moreover, the nonuniform presence of such materials distributed in the grain beds further complicates the air flow distribution. Because of the complex nature of heterogeneous and nonuniform grain systems, this topic has been studied for many years, and yet, it is still an interesting area of study.

Two major numerical methods, finite difference and finite element methods, have been used for the investigation on the pressure and air flow patterns. Many types of constitutive equations of pressure gradient and velocity have been proposed and experimented in the literature. The diversity in the format of the constitutive equations as well as the appropriate choice of numerical schemes determines the approaches to the simulation methods.

Brooker (1961) developed a finite difference model of two dimensional, incompressible air flow in grain beds. He combined the steady state continuity equation and an empirical constitutive equation of pressure gradient and velocity to form a nonlinear partial differential equation in pressure. The comparison between the predicted and measured pressure patterns was good. A different type of constitutive equation was used by Bunn and Hukill (1963) for the numerical calculations of pressure in porous media. Brooker (1969) considered the nonlinear velocity-pressure constitutive equation in his numerical model. Jindal and Thompson (1972) applied Brooker's method to two dimensional triangular-shaped piles of sorghum. Pierce and Thompson (1975) extended Brooker's method and derived a differential equation for air flow patterns in cylindrical coordinate grain systems. Marchant (1976a) also employed Brooker's method for the prediction of pressure distribution in large hay bales.

The application of finite element analysis to solve air flow distribution in grain beds was introduced by Marchant (1976b). Segerlind (1982) re-studied Brooker's (1969) nonlinear air flow equation by using finite element method. Rumsey and Fortis (1984) applied two dimensional finite element analysis to improve air flow distribution in a batch walnut dryer. The advantages of finite element method in manipulating the boundary was successfully illustrated in his work. Smith (1982) developed a three dimensional finite element procedure to predict velocity and pressure patterns in grain and hay beds.

Haque et al. (1981) investigated the heterogeneous grain beds where a nonuniform distribution of fines existed. They used finite difference method and a constitutive equation in which a term of nonuniform distribution of fines was included. Rumsey (1985) extended Brooker's equation (1961) to accommodate an anisotropic model for air flow in beds of rice. Lai (1980) used Ergun's equation as the required constitutive equation, and also introduced stream function as the primary variable in the final governing differential equation. His approach is different from those in the above studies in which pressure was arranged as the primary variable. In his work, nonuniform grain beds of two different bed porosities were studied.

THEORY AND METHOD

In this study, a finite difference approach was developed to predict the air flow patterns in nonuniform and heterogeneous grain beds. A constitutive equation of pressure gradient and velocity is expressed in a vector form as

$$\underset{\sim}{\nabla}P = -C(x, y)\,V^{n}\,\underset{\sim}{b} \qquad [1]$$

where $\underset{\sim}{\nabla}P$ is pressure gradient, $C(x, y)$ is a spatial function in 2-dimensional domain, V and $\underset{\sim}{b}$ are the magnitude and direction of superficial velocity, $\underset{\sim}{V}$, respectively. Equation [1] can be rewritten as

$$\underset{\sim}{V} = -A(x, y)\,|\underset{\sim}{\nabla}P|^{\frac{1-n}{n}}\,\underset{\sim}{\nabla}P \qquad [2]$$

where $A(x, y) = [C(x, y)]^{\frac{-1}{n}}$, $|\underset{\sim}{\nabla} P|$ is the magnitude of $\underset{\sim}{\nabla} P$.

Assuming that the air flow is incompressible, the continuity equation becomes

$$\underset{\sim}{\nabla} \cdot \underset{\sim}{V} = 0 \qquad [3]$$

Substitution of Equation 2 in Equation 3 gives the following governing differential equations of air flow:
for Cartesian coordinates,

$$\left\{\left[\frac{\partial P}{\partial x}\right]^2 + \left[\frac{\partial P}{\partial y}\right]^2\right\}\left\{\frac{\partial A}{\partial x}\cdot\frac{\partial P}{\partial x} + \frac{\partial A}{\partial y}\cdot\frac{\partial P}{\partial y} + A\left[\frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2}\right]\right\}$$
$$- 2mA\left\{\left[\frac{\partial P}{\partial x}\right]^2\cdot\frac{\partial^2 P}{\partial x^2} + 2\,\frac{\partial P}{\partial x}\cdot\frac{\partial P}{\partial y}\cdot\frac{\partial^2 P}{\partial x\partial y} + \left[\frac{\partial P}{\partial y}\right]^2\cdot\frac{\partial^2 P}{\partial y^2}\right\} = 0 \qquad [4]$$

for cylindrical coordinates,

$$\left\{\left[\frac{\partial P}{\partial r}\right]^2 + \left[\frac{\partial P}{\partial z}\right]^2\right\}\left\{\frac{\partial A}{\partial r}\cdot\frac{\partial P}{\partial r} + \frac{\partial A}{\partial z}\cdot\frac{\partial P}{\partial z} + A\left[\frac{\partial^2 P}{\partial r^2} + \frac{1}{r}\cdot\frac{\partial P}{\partial r} + \frac{\partial^2 P}{\partial z^2}\right]\right\}$$
$$- 2mA\left\{\left[\frac{\partial P}{\partial r}\right]^2\cdot\frac{\partial^2 P}{\partial r^2} + 2\,\frac{\partial P}{\partial r}\cdot\frac{\partial P}{\partial z}\cdot\frac{\partial^2 P}{\partial r\partial z} + \left[\frac{\partial P}{\partial z}\right]^2\cdot\frac{\partial^2 P}{\partial z^2}\right\} = 0 \qquad [5]$$

where $m = (1 - 1/n)/2$.

Note that, in the above equations, the coefficient A is a function of space, not a constant through the entire bed region, this is the major difference from Brooker's equation (1961, 1969). The central difference approximations were used to evaluate the derivatives of pressure, P, and coefficient A. This procedure reduced Equation 4 or 5 into a finite difference equation. A successive over-relaxation method (Marchant, 1975 and 1976a) was used to sweep the grid points and calculated the pressures. The superficial velocity can then be obtained by Equation 2.

As an illustration, the constitutive equation which was proposed by Jung (1987) was used in this study,

$$\Delta P = C\,\rho^{c1}\,(1 + Fm)^{c2} H^{c3}\,V^n \qquad [6]$$

where

ΔP = pressure drop of entire height, Pa
ρ = bulk density of shelled corn, Kg/m^3
Fm = amount of fines, expressed as a decimal
H = height of material, m
V = superficial velocity, m/s
C, C1, C2, C3, and n are constants

The above empirical equation was obtained at the low velocity range from 0.001 to 0.008 m/s, and the values of constants are C=6.88E-15, C1=5.92, C2=10.28, C3=1.04, and n=1.02 (Jung, 1987).

Since the value of C3 is very close to 1, and the effect of material height is mainly due to the density change upon the compact of the material, Equation 6 may be written as

$$\Delta P/H = [C\,\rho^{c1}(1 + F_m)^{c2}]\;V^n \qquad [7]$$

$$\text{or}\quad \Delta P/H = C(x, y)\,V^n \qquad [8]$$

Equation 7 or 8 is the scalar form of Equation 1. Although a constitutive equation at low flow range was used in this study, the theory is valid for other consitutive equations at higher velocities as long as they can be expressed in the form of Equation 1 or 2. In fact, when A is a constant, Equation 2 is the vector form of Shedd's equation,

$$V = A\left[\frac{\partial P}{\partial n} \right]^B \quad [9]$$

RESULTS AND DISCUSSION

For an axisymmetric cylindrical grain bed, Equation 5 can be used and the numerical procedure as discussed in the Section of Theory was followed. The numerical calculations were verified by being compared with the experimental pressure data. Boundary conditions used, as shown in Figure 1, were constant pressure along the bottom of the bed, constant zero pressure along the top of the bed, and no flow across lateral side and center line. Figure 2 indicates a good agreement between the calculated and measured static pressure in a bed of shelled corn with homogeneous and uniform distribution.

Two basic types of simulations were conducted on air flow patterns in the beds of shelled corn. They are

(1) Homogeneous bed with nonuniform corn density distribution,

(2) Heterogeneous bed which consists of clean shelled corn and fines.

The simulations were carried out for the grain bins where the inlet of air is directed at the center region of the floor. The schematic diagram with the boundary conditions is given in Figure 3. Two regions were arranged in the grain bed to accommodate the heterogeneity and nonuniformity for two specific cases studied (Figure 4). For both Cases A and B, the region near the center line exhibits higher air flow resistance. The followings are the detailed discussion and results.

(1) HOMOGENEOUS BED WITH NONUNIFORM CORN DENSITY DISTRIBUTION

To illustrate how the nonuniform distribution of grain influence the air flow patterns, the following basic parameters are chosen for both Cases A and B,

Region I:
FM = 0% (clean shelled corn)
ρ = 800 Kg/m^3

Region II:
Fm = 0% (clean shelled corn)
ρ = 750 Kg/m^3

In Figure 5 and 6, pressure contour and velocity field of a homogeneous and uniform bed as shown in Figure 3 are presented, these two plots are regarded as references for the purposes of comparison. The density of corn in the whole bed is 750 Kg/m^3. The nonuniformity of density distribution in Cases A and B shows different pressure and velocity patterns, which are given in Figures 7 through 10. The pressure and coordinates are arranged in the dimensionless forms. As shown in Figures 7 and 8, the pressure patterns are shifted toward to the air inlet (i.e. lower left corner) of the bed due to the higher air flow resistance in the region I for both cases. The magnitudes of velocity vectors in Figures 6, 9 and 10 have been scaled to a proper size, and the velocity vectors in a same field or plot are relative in size. Bigger magnitude in one plot than that in another plot does not imply higher velocity. Although the patterns of velocity fields look similar, the velocities are higher in the uniform bed (Figure 6).

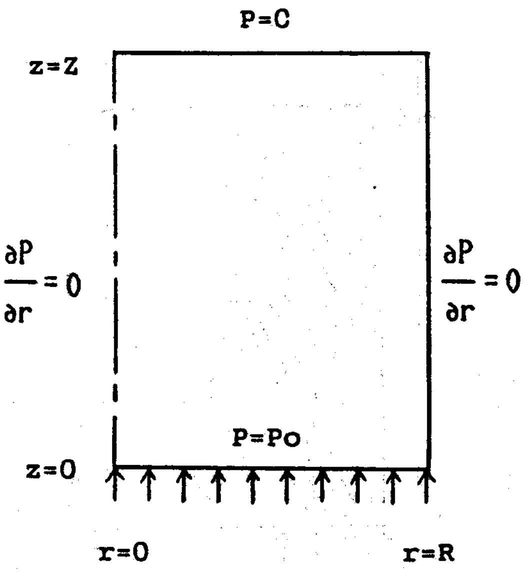


Fig. 1. A cylindrical grain bed and boundary conditions.

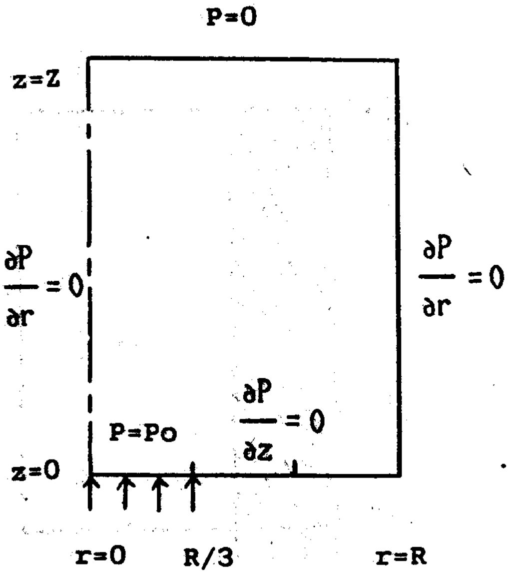


Fig. 3. A cylindrical grain bed with centered air inlet and boundary conditions.

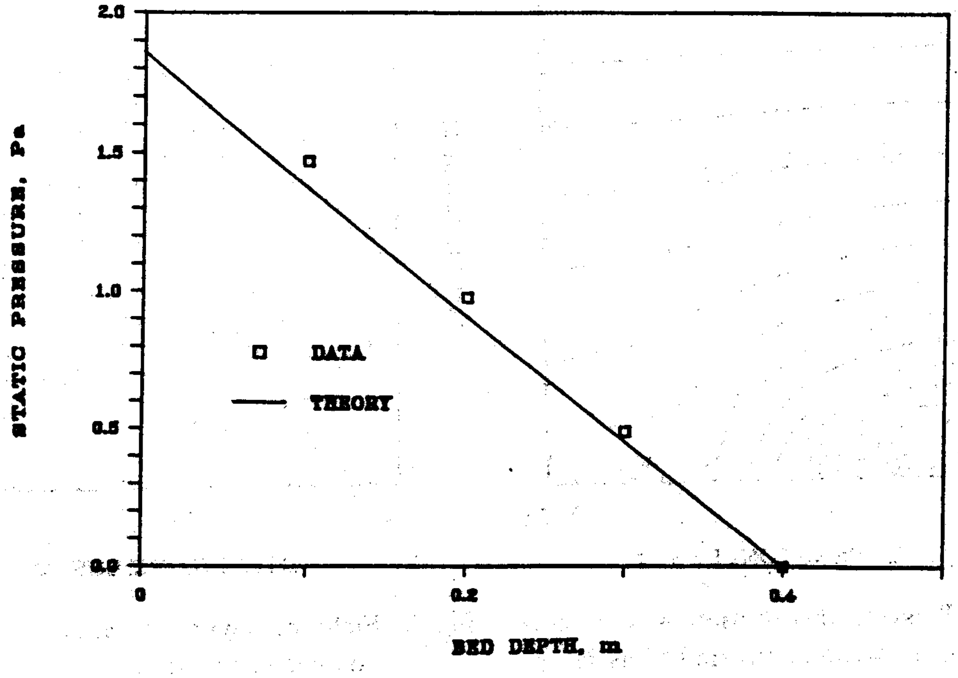


Fig. 2. Comparison of calculated and measured static pressure.

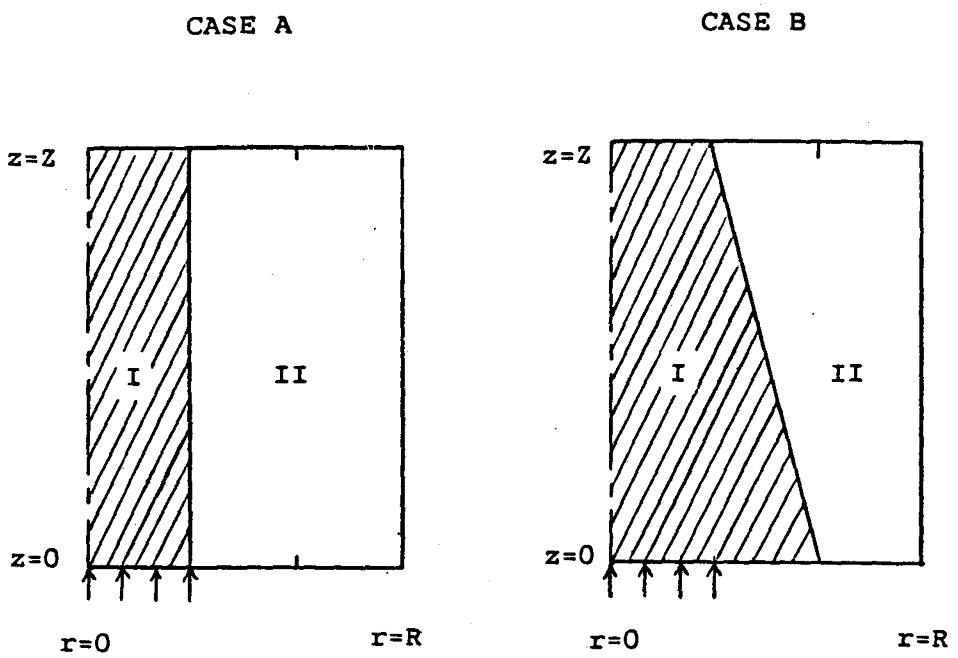
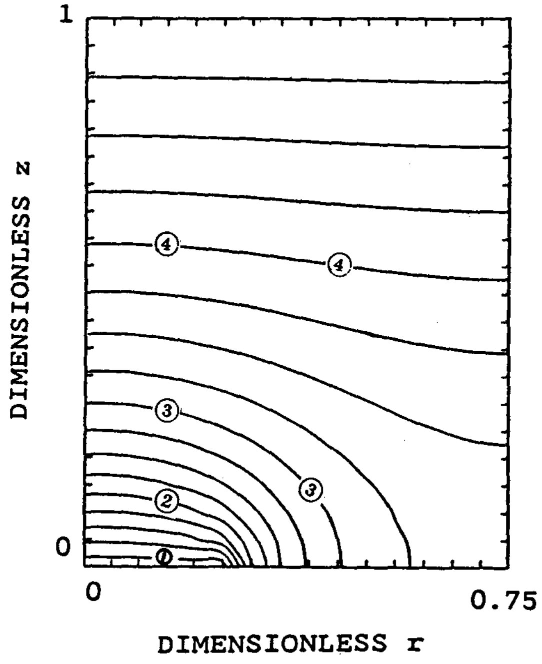


Fig. 4. Grain beds of two regions, Cases A and B.



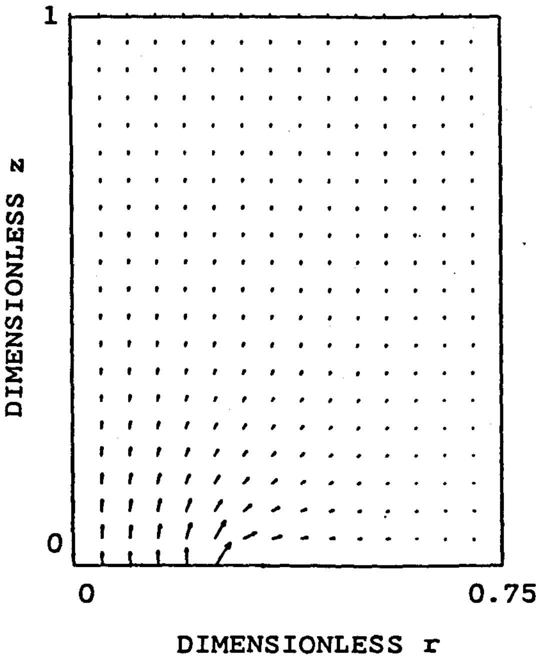


Fig. 5. Pressure distribution in a homogeneous and uniform bed as shown in Figure 3. Note ①: 0.96, ②: 0.72, ③: 0.48, ④: 0.24.

Fig. 6. Field of superficial velocity in a homogeneous and uniform bed as shown in Figure 3.

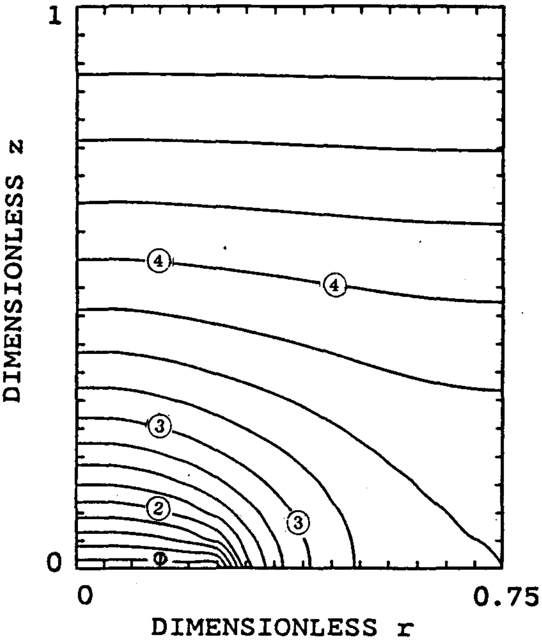


Fig. 7. Pressure distribution in a homogeneous and nonuniform bed, Case A. Note ①: 0.96, ②: 0.72, ③: 0.48, ④ 0.24.

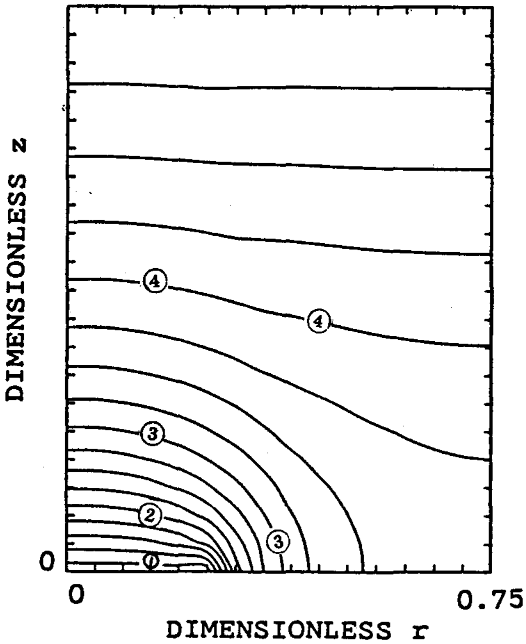


Fig. 8. Pressure distribution in a homogeneous and nonuniform bed, Case B. Note ①: 0.96, ②: 0.72, ③: 0.48, ④: 0.24.

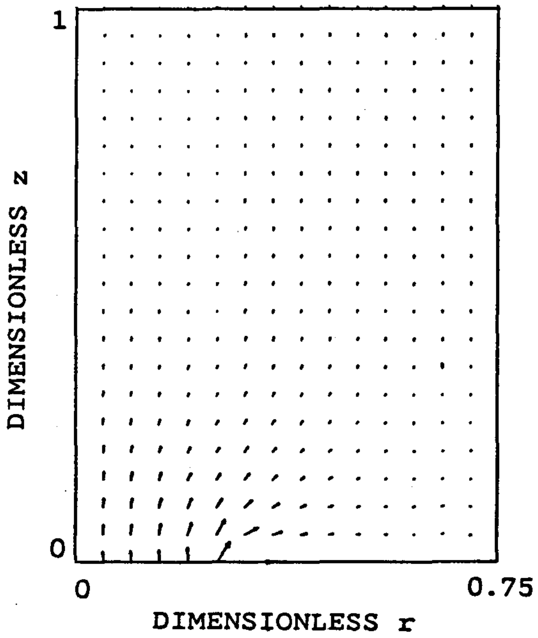


Fig. 9. Field of superficial velocity in a homogeneous and nonuniform bed, Case A.

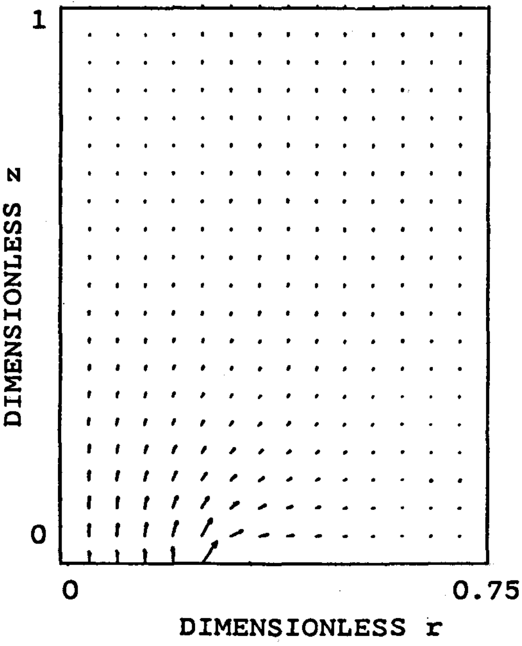


Fig. 10. Field of superficial velocity in a homogeneous and nonuniform bed, Case B.

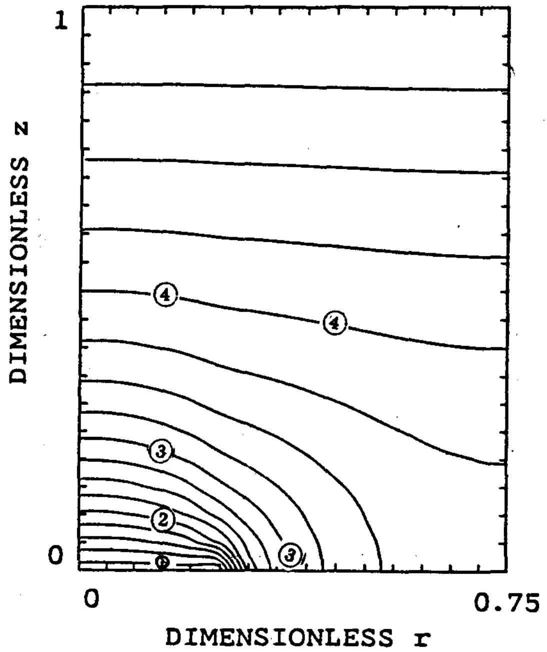


Fig. 11. Pressure distribution in a heterogeneous bed, Case A. Note ①: 0.96, ②: 072, ③: 0.48, ④: 0.24.

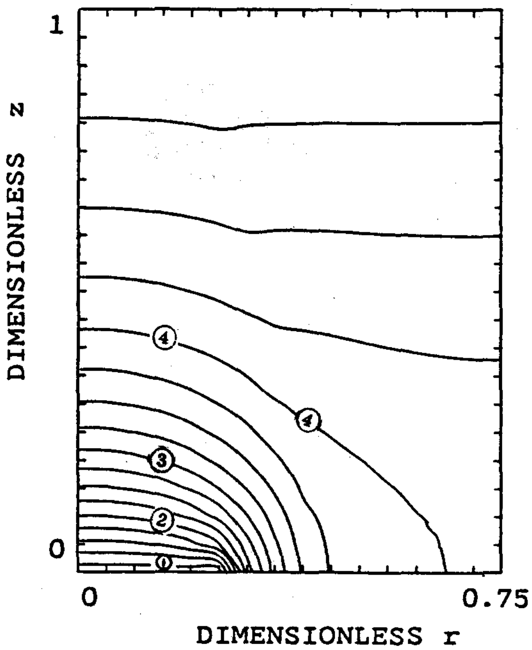


Fig. 12. Pressure distribution in a heterogeneous bed, Case B. Note ①: 0.96, ②: 0.72, ③: 0.48, ④: 0.24.

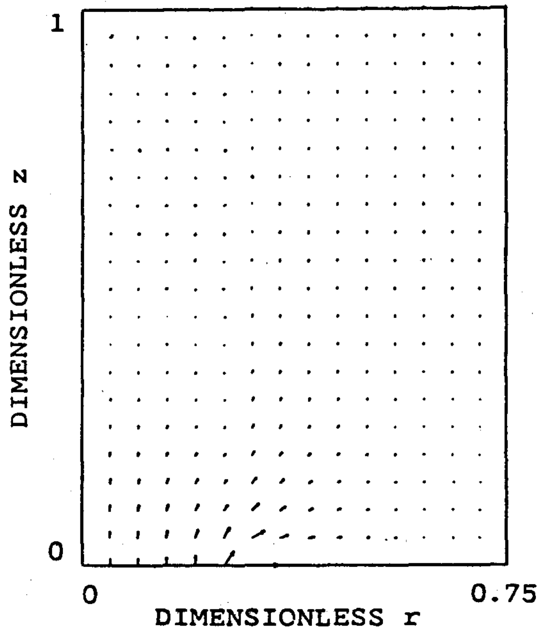


Fig. 13. Field of superficial velocity in a heterogeneous bed, Case A.

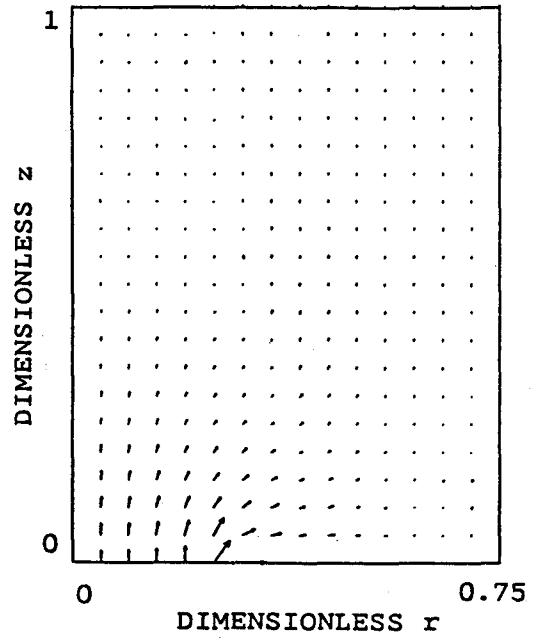


Fig. 14. Field of superficial velocity in a heterogeneous bed, Case B.

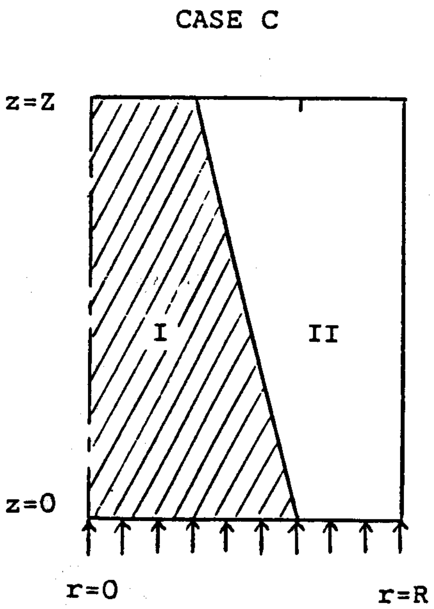


Figure 15. Grain bed of two regions, Case C.

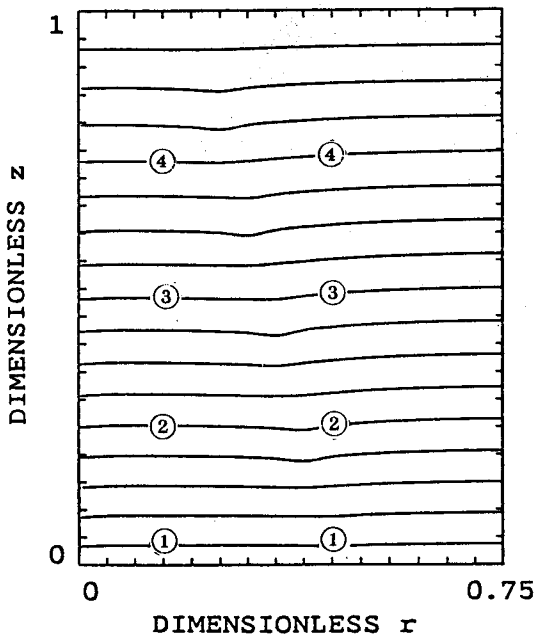


Fig. 16. Pressure distribution in a heterogeneous bed, Case C. Note ①: 0.96, ②: 072, ③: 0.48, ④: 0.24.

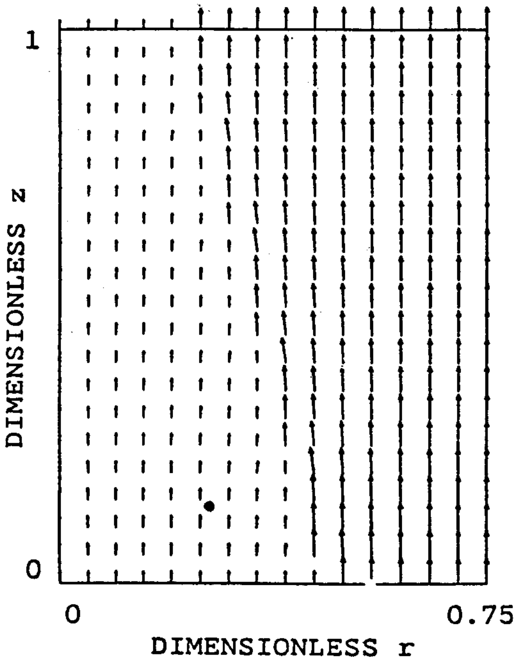


Fig. 17. Field of superficial velocity in a heterogeneous bed, Case C.

(2) HETEROGENEOUS BED WHICH CONSISTS OF CLEAN SHELLED CORN AND FINES

Here are some basic parameters for both cases A and B,

Region I: $F_m = 7\%$
$\rho = 762$ Kg/m^3

Region II: $F_m = 0\%$
$\rho = 748$ Kg/m^3

The pressure and velocity distribution to account for the heterogeneity in Cases A and B are shown in Figures 11 through 14. Similar observation has been found in these four figures when compared with those of the homogeneous and nonuniform grain beds (Figures 7 through 10). Since the presence of 7% fines in the region I, much higher air flow resistance is expected. Higher pressure-drop occurs when air flow crosses the region I, thus the shift of pressure patterns toward the air inlet is more obvious.

To show the effect of heterogeneity on the air flow distribution, Case C as shown in Figure 15 was considered, where a constant pressure along the entire bed bottom was assigned as a boundary condition. Same parameters as given above were used, and pressure and velocity plots are presented in Figure 16 and 17. For a comparison, Figure 18 and 19 present the pressure and velocity distribution of a homogeneous and uniform bed (Figure 1). The heterogeneity causes the pressure contours inclined downward at left (i.e. at r=0) because of higher resistance in the

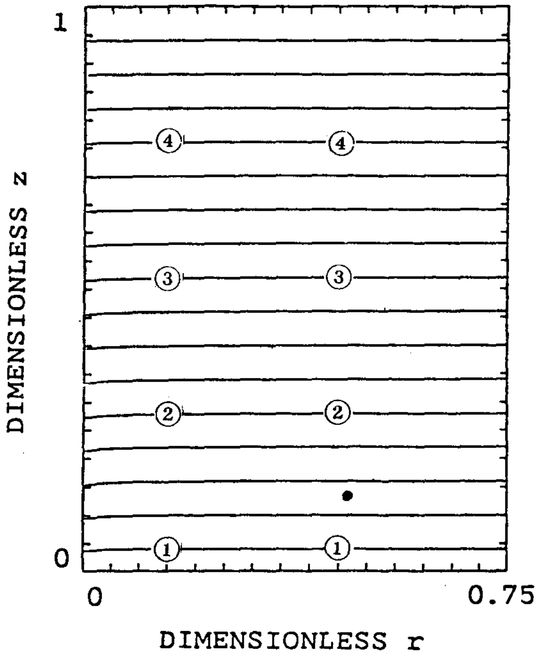


Fig. 18. Pressure distribution in a homogeneous and uniform bed as shown in Figure 1. Note ①: 0.96, ②: 0.72, ③: 0.48, ④: 0.24.

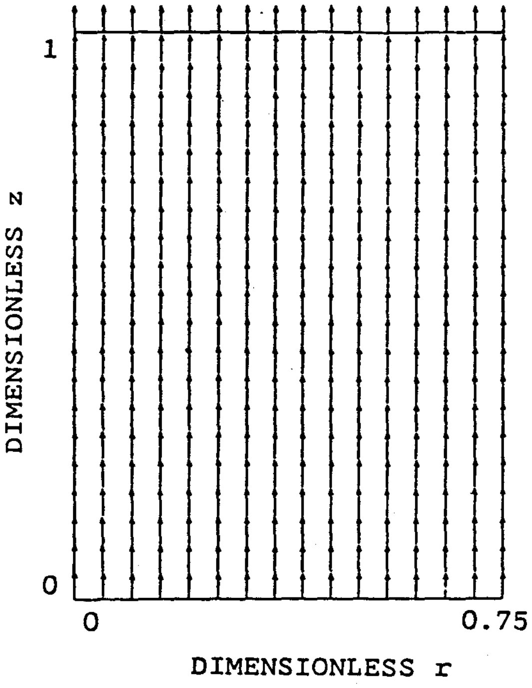


Fig. 19. Field of superficial velocity in a homogeneous and uniform bed as shown in Figure 1.

region I. The velocity field, Figure 17, shows that higher velocities exist in the region II where clean shelled corn is less resistant to air flow. The comparison of Figures 17 and 19 fully illustrates the effect of heterogeneity on the uniform air distribution. On the other hand, the comparison of Figures 14 and 17 also indicates that a different arrangement of air inlet can contribute to more uniform air distribution in the bed. This observation implies that nonuniform air flow distribution in the grain bed can be improved if physical conditions of bed are adjusted. Rumsey (1984) has demonstrated this possibilities for a bath walnut dryer. Therefore, the computer simulation is of great importance in designing the grain storage and drying operations.

CONCLUSIONS

The uniform distribution of air flow in grain beds highly depends on the intrinsic nature of the beds. Nonuniformity and heterogeneity are the two common situations encountered in grain storage. A numerical scheme for air flow distribution in both homogeneous and heterogeneous grain systems has been developed. The simulations show that the heterogeneity and nonuniformity of grain beds play important roles in the uniform distribution of air flow. In addition, nonuniform air flow distribution in the grain bed can be improved if physical conditions of the bed are adjusted.

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