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ON NUMERICAL SIMULATION OF A CROSSFLOW MOVING BED HEAT EXCHANGER: AN UNIFIED NUMERICAL METHOD AND APPLICATIONS.

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ABSTRACT

Fixed and moving granular beds exchangers are often used in industrial applications. In the present paper, a general schemes, solving for the problem of two phases in a process of crossflow moving bed heat transfer and transport, is done. Modelization of these problems consist on two transient equations of convection-diffusion, couples, where the temperatures of both phases are the variables which have to be computed. Some numerical schemes implicit and explicit are involved for the resolution using finite elements, A strategy of mesh updating is proposed to improve the numerical solution. Finally; numerical results is shown for a crossflow moving bed heat exchanger (MBHE), which is a suitable equipment to heat recovery.

INTRODUCTION

During the last decade the restrictions on cleaning industrial waste gases have been strengthened. At the same time high energy costs have made it favorable to recover energy from hot industrial gases.

In many industrial processes, after of high technology, it is interesting to separate particles from a liquid or gaseous fluid by circulating through a filter which retains the particles.

-The moving bed Heat exchanger are commonly used as energy storage system in different applications. The objetive of this paper is to develop a mathematical modeling for the simulation of such system, which will aid in their design, operation and control.

We present a numerical solution for the model, that is formulated as two coupled convection-diffusion equations for the solid and fluid phases

Figure 1 shows a moving heat exchanger-filter (MBHE). In the upper unit, cold particles enter and fall down. Laterally, a hot gas carrying particles is cooled when it passes through the layer of particles which is moving downwards.

ANALYSIS AND MODELING OF THE TRANSIENT TEMPERATURE

The two dimensional model of a crossflow heat exchanger used in this study is an extension of an existing heat transfer model given by (Schmidt et al., 1981).

In the model the following assumptions have been made:

- Constant fluid and material properties
- Uniform heat transfer coefficient
- Uniform initial temperature distribution in the solid material
- Constant fluid and solid velocity

The transient response of the Crossflow Heat Exchanger is governed by the following equations,

Fluid phase:

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}=\frac{h\,a}{p_f c_f \varepsilon}(\theta-T)+\frac{K_{ef}}{p_f c_f}\left(\frac{\partial^2 T}{\partial x^2}\right) \qquad (1)$$

Solid phase:

$$\frac{\partial \theta}{\partial t}+v\frac{\partial \theta}{\partial y}=\frac{K_{es}}{p_s c_s}\left(\frac{\partial^2 \theta}{\partial y^2}\right)+\frac{h\,a}{p_s c_s(1-\varepsilon)}(T-\theta) \qquad (2)$$

Boundary Conditions:

The boundary conditions at the inlet and outlet must be specified for the computational scheme. The solid and fluid temperatures at the inlet faces of the MBHE are known. For the outlet faces of the MBHE, we have used the following convective boundary conditions,

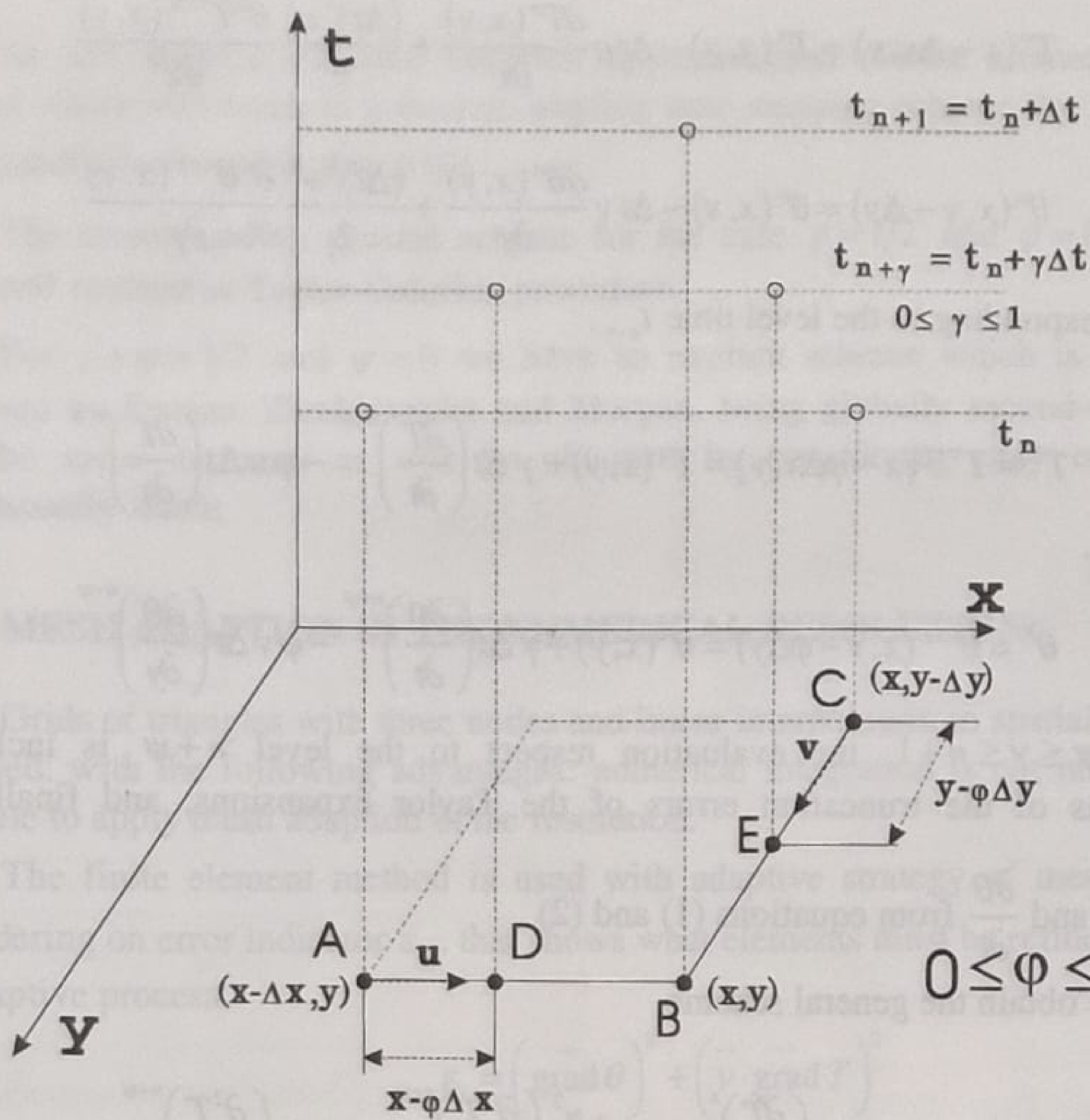
$$-K_{es}\frac{\partial \theta}{\partial y}=h_T(\theta-T_0)$$

$$-K_{ef}\frac{\partial T}{\partial x}=h_T(T-T_0)$$

NUMERICAL SOLUTION AN UNIFIED METHOD

The algorithm proposed consist in a development unified the procedures with discretization in time before attempting the spatial discretization, using an scheme along the characteristic for both phases fluid and solid. Its derivation involves a local Taylor expansion in the approximation of the total derivative in the direction of the flow and to consider the following scheme with two parameters in the evaluation of the terms not belong to the total derivative (C and D in the figure) where the solid phase the characteristics line is $\overline{CB}$ and the fluid phase with characteristics line $\overline{AB}$ which are corresponding to:

$$\frac{dx}{dt}=u \quad and \quad \frac{dy}{dt}=v$$



thus we replace the equations (1) and (2) by the followings,

$$\frac{dT}{dt} = \alpha_1(\theta^* - T^*) + \beta_1\left(\frac{\partial^2 T^{n+\gamma}}{\partial x^2}\right)$$

$$\frac{d\theta}{dt} = \alpha_2(T^* - \theta^*) + \beta_2\left(\frac{\partial^2 \theta^{n+\gamma}}{\partial y^2}\right)$$

being α_1, α_2, β_1 and β_2 the coefficients appearing multiplying to the right hand side of the equations (1) and (2). We consider

$$\theta^* = \theta^{n+\gamma}(y - \varphi\Delta y) = \theta^{n+\gamma}(E)$$

$$T^* = T^{n+\gamma}(x - \varphi\Delta x) = T^{n+\gamma}(D)$$

and the following approximations for the total derivatives,

$$\frac{dT}{dt} \approx \frac{T^{n+1}(x,y) - T^n(x - \Delta x, y)}{\Delta t}$$

$$\frac{d\theta}{dt} \approx \frac{\theta^{n+1}(x,y) - \theta^n(x, y - \Delta y)}{\Delta t}$$

The temperature for both particles fluids and solids corresponding to the level time t_n by means of local Taylor expansion gives,

$$T^n(x-\Delta x, y) = T^n(x,y) - \Delta t\, u \frac{\partial T^n(x,y)}{\partial x} + \frac{(\Delta t)^2 u^2}{2} \frac{\partial^2 T^{n+\psi}(x,y)}{\partial x^2}$$

$$\theta^n(x, y-\Delta y) = \theta^n(x,y) - \Delta t\, v \frac{\partial \theta^n(x,y)}{\partial y} + \frac{(\Delta t)^2 v^2}{2} \frac{\partial^2 \theta^{n+\psi}(x,y)}{\partial y^2}$$

and corresponding to the level time $t_{n+\gamma}$,

$$T^* = T^{n+\gamma}(x-\varphi\Delta x, y) = T^n(x,y) + \gamma\, \Delta t \left(\frac{\partial T}{\partial t}\right)^{n+\psi} - \varphi\, u\, \Delta t \left(\frac{\partial T}{\partial x}\right)^{n+\psi}$$

$$\theta^* = \theta^{n+\gamma}(x, y-\varphi\Delta y) = \theta^n(x,y) + \gamma\, \Delta t \left(\frac{\partial \theta}{\partial t}\right)^{n+\psi} - \varphi\, v\, \Delta t \left(\frac{\partial \theta}{\partial y}\right)^{n+\psi}$$

where $\psi \le \gamma \le n+1$, the evaluation respect to the level $n+\psi$ is including approximations of the truncation errors of the Taylor expansions, and finally we substitute $\frac{\partial T}{\partial t}$ and $\frac{\partial \theta}{\partial t}$ from equations (1) and (2)

Thus we obtain the general scheme,

$$T^{n+1} - T^n + \Delta t\, u \left(\frac{\partial T}{\partial x}\right)^n - (\Delta t)^2 \frac{u^2}{2} \left(\frac{\partial^2 T}{\partial x^2}\right)^{n+\psi} - \Delta t\, \beta_1 \left(\frac{\partial^2 T}{\partial x^2}\right)^{n+\psi} =$$
$$\alpha_1 \Delta t(\theta^n - T^n) + (\Delta t)^2 \gamma (T-\theta)^{n+\psi} \left[\alpha_1^2 + \alpha_1\alpha_2\right] +$$
$$\alpha_1 u (\Delta t)^2 (\gamma+\varphi) \left(\frac{\partial T}{\partial x}\right)^{n+\psi} - \alpha_1 (\Delta t)^2 \beta_1 \gamma \left(\frac{\partial^2 T}{\partial x^2}\right)^{n+\psi} -$$
$$\alpha_1 v (\Delta t)^2 (\gamma+\varphi) \left(\frac{\partial \theta}{\partial y}\right)^{n+\psi} + \alpha_1 (\Delta t)^2 \beta_2 \gamma \left(\frac{\partial^2 \theta}{\partial y^2}\right)^{n+\psi}$$

and,

$$\theta^{n+1} - \theta^n + \Delta t\, v \left(\frac{\partial \theta}{\partial y}\right)^n - (\Delta t)^2 \frac{v^2}{2} \left(\frac{\partial^2 \theta}{\partial y^2}\right)^{n+\psi} - \Delta t\, \beta_2 \left(\frac{\partial^2 \theta}{\partial y^2}\right)^{n+\psi} =$$
$$\alpha_2 \Delta t(T^n - \theta^n) + (\Delta t)^2 \gamma (\theta-T)^{n+\psi} \left[\alpha_2^2 + \alpha_1\alpha_2\right] +$$
$$\alpha_2 v (\Delta t)^2 (\gamma+\varphi) \left(\frac{\partial \theta}{\partial y}\right)^{n+\psi} - \alpha_2 (\Delta t)^2 \beta_2 \gamma \left(\frac{\partial^2 \theta}{\partial y^2}\right)^{n+\psi} -$$
$$\alpha_2 u (\Delta t)^2 (\gamma+\varphi) \left(\frac{\partial T}{\partial x}\right)^{n+\psi} + \alpha_2 (\Delta t)^2 \beta_1 \gamma \left(\frac{\partial^2 T}{\partial x^2}\right)^{n+\psi}$$

At this stage a standard Galerkin approximation (Finite element method) is applied which will result in a discrete implicit time-stepping scheme that is expected to be unconditionally stable if $\psi \geq 1/2$.

The corresponding general scheme for the case $\gamma = 1/2$ and $\varphi = 0$ is a Lax and Wendroff method or Taylor-Galerkin procedure.

For $\gamma + \varphi = 1/2$ and $\psi = 0$ we have an explicit scheme which is similar to the proposed by Peraire, Zienkiewickz and Morgan, being globally second-order accurate and the same accuracy as will be obtained by considering only convection but conditionally stable.

MESH ADAPTION IN THE NUMERICAL RESOLUTION:

Grids of triangles with three nodes and linear interpolation in spatial discretization are used, with the following advantages: numerical integration is not needed and it is possible to apply mesh adaption in the resolution.

The finite element method is used with adaptive strategy of mesh refinement, considering on error indicator ε_i , that shows what elements must be refined in each step of adaptive process,

$$\varepsilon_i = \left(\vec{\text{grad}}\,\theta\right)^2 + \left(\vec{v}\cdot\vec{\text{grad}}\,T\right)^2$$

This indicator is used small velocities of the solid phase, as they are in our case.

When the distribution of error indicator, ε_i , is known in the grid, a new mesh is generated from a set of points obtained by inserting or deleting nodes in the mesh before.

In this work, a technique of mesh refinement that performs non structured grids.

We have considered the following criteria of mesh adaption, being ε_i the error indicator for Ω_i :

1.- $\varepsilon_i \leq a\varepsilon_{max}$, the three nodes of the element are deleted, except for those which belong to the boundary definition.

2.- $a\varepsilon_{max} < \varepsilon_i \leq b\varepsilon_{max}$, a new point instead in the center of the triangle, is considered.

3.- $b\varepsilon_{max} < \varepsilon_i \leq c\varepsilon_{max}$, the three nodes of the triangles and the point before are considered.

4.- $c\varepsilon_{max} < \varepsilon_i \leq d\varepsilon_{max}$, the three nodes of the triangles are considered and three new ones allocate in the middle of each side of the triangle.

5.- $d\varepsilon_{max} < \varepsilon_i \leq e\varepsilon_{max}$, two steps of the case 4 are considered.

Being a, b, c, d, e, parameters chosen for different problems:

$$0 \leq a < b < c < d < e \leq 1$$

FIGURE CAPTIONS

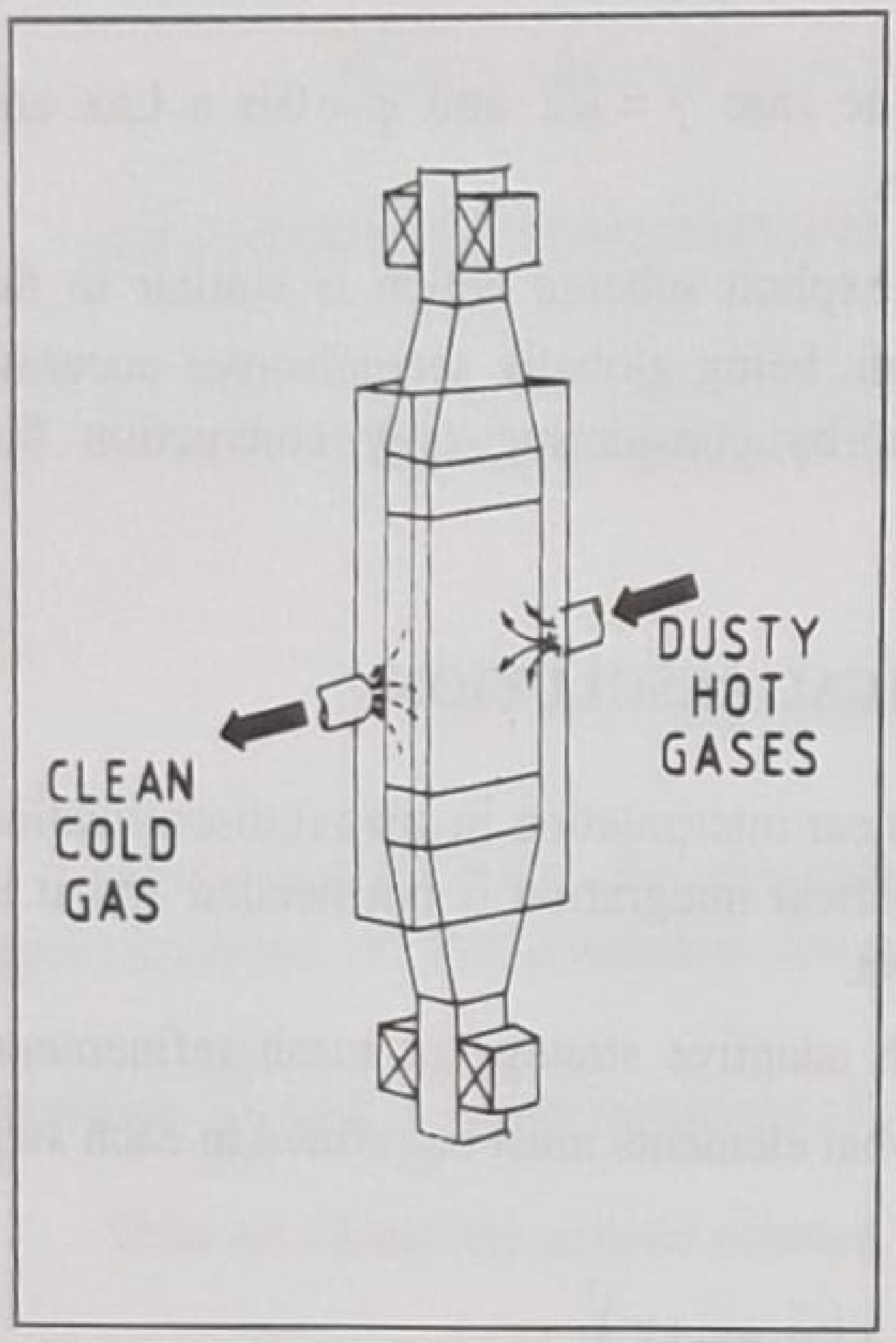


Fig. 1: Schematic Diagram of a Crossflow Moving Bed Heat Exchange-Filter (MBHE)

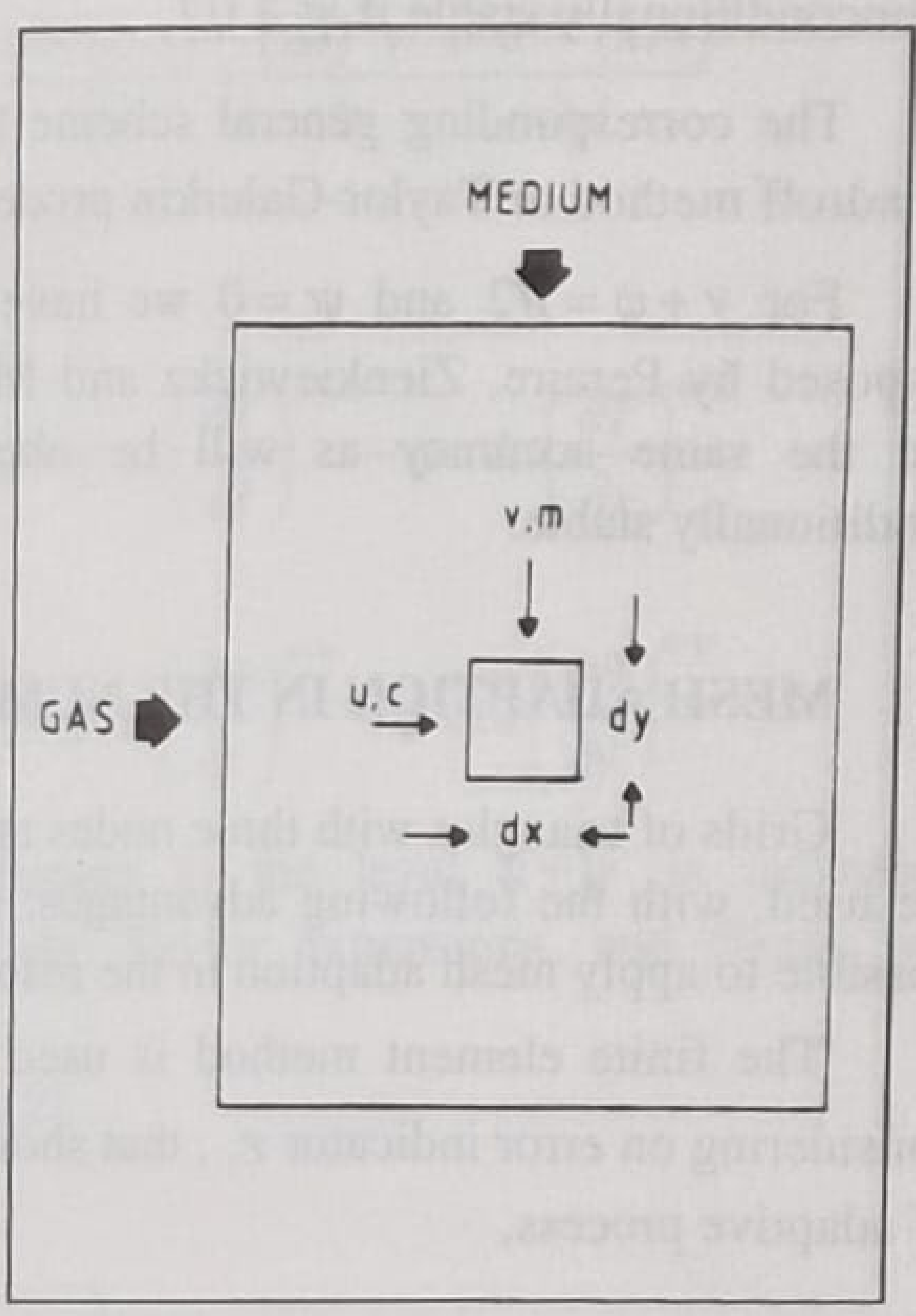


Fig.2: Elemental dxdy of bed for calculating dust collection.

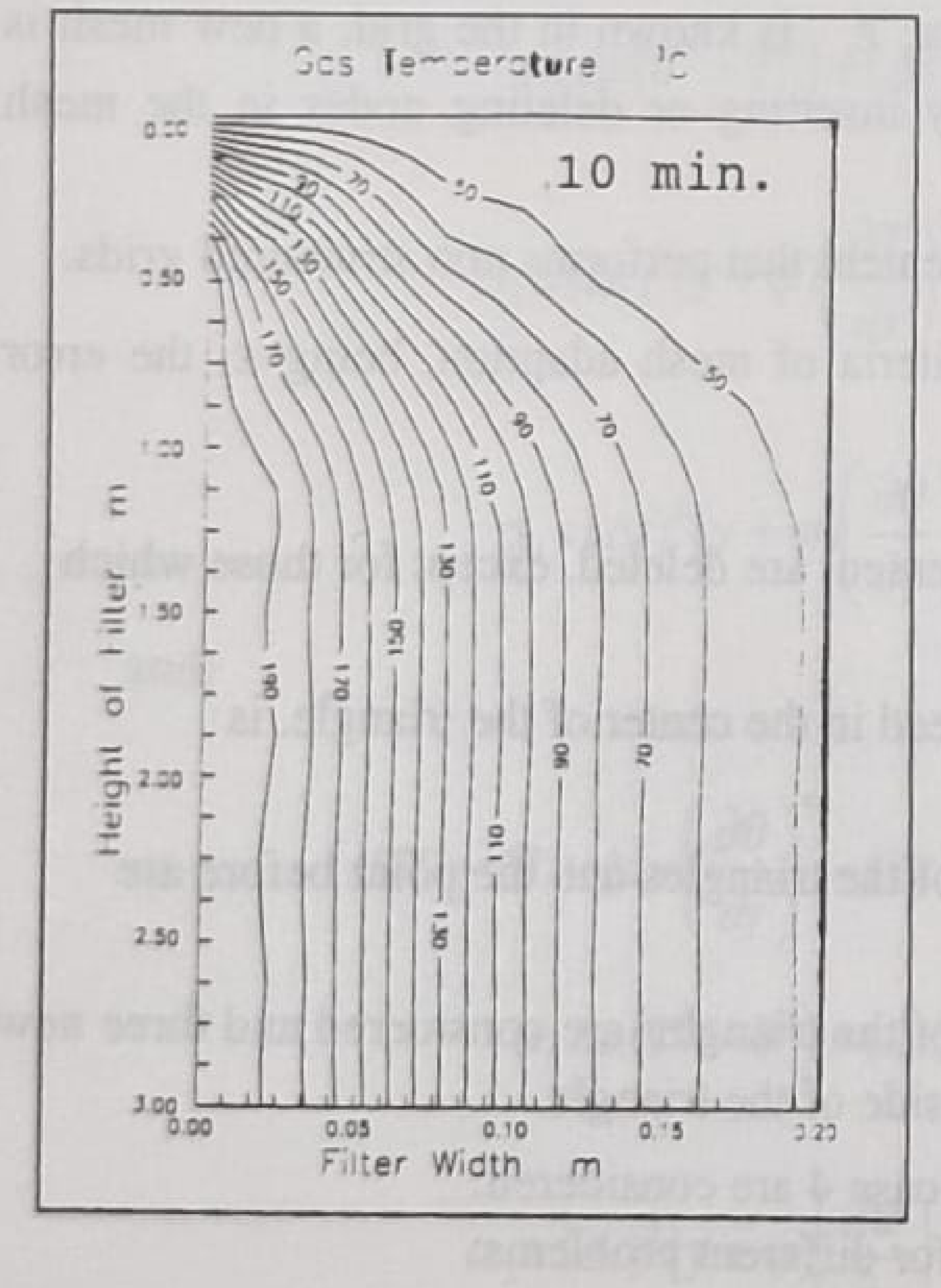


Fig. 3: Gas temperature distribution in the MBHE for t = 10 min.

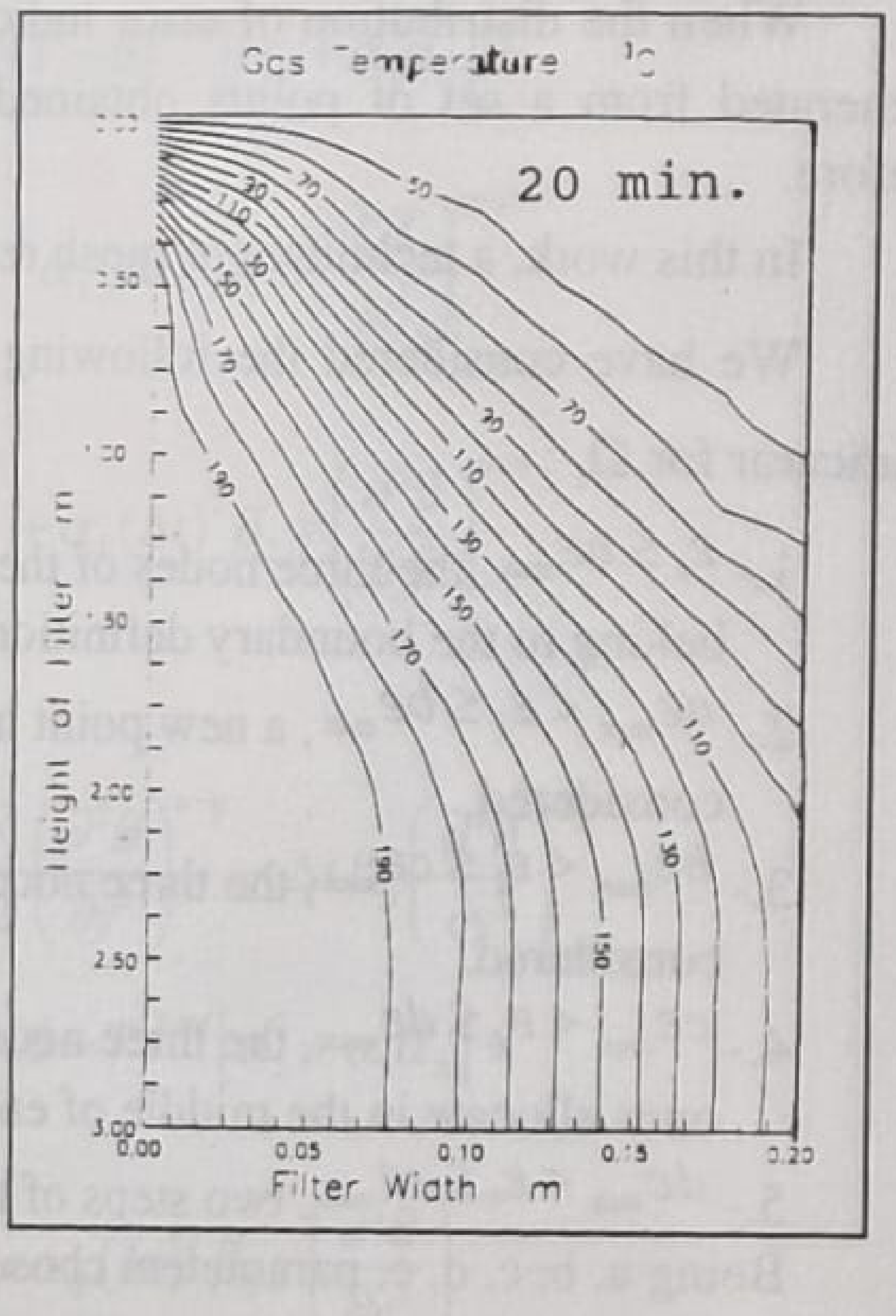


Fig. 4: Gas temperature distribution in the MBHE for t = 20 min.

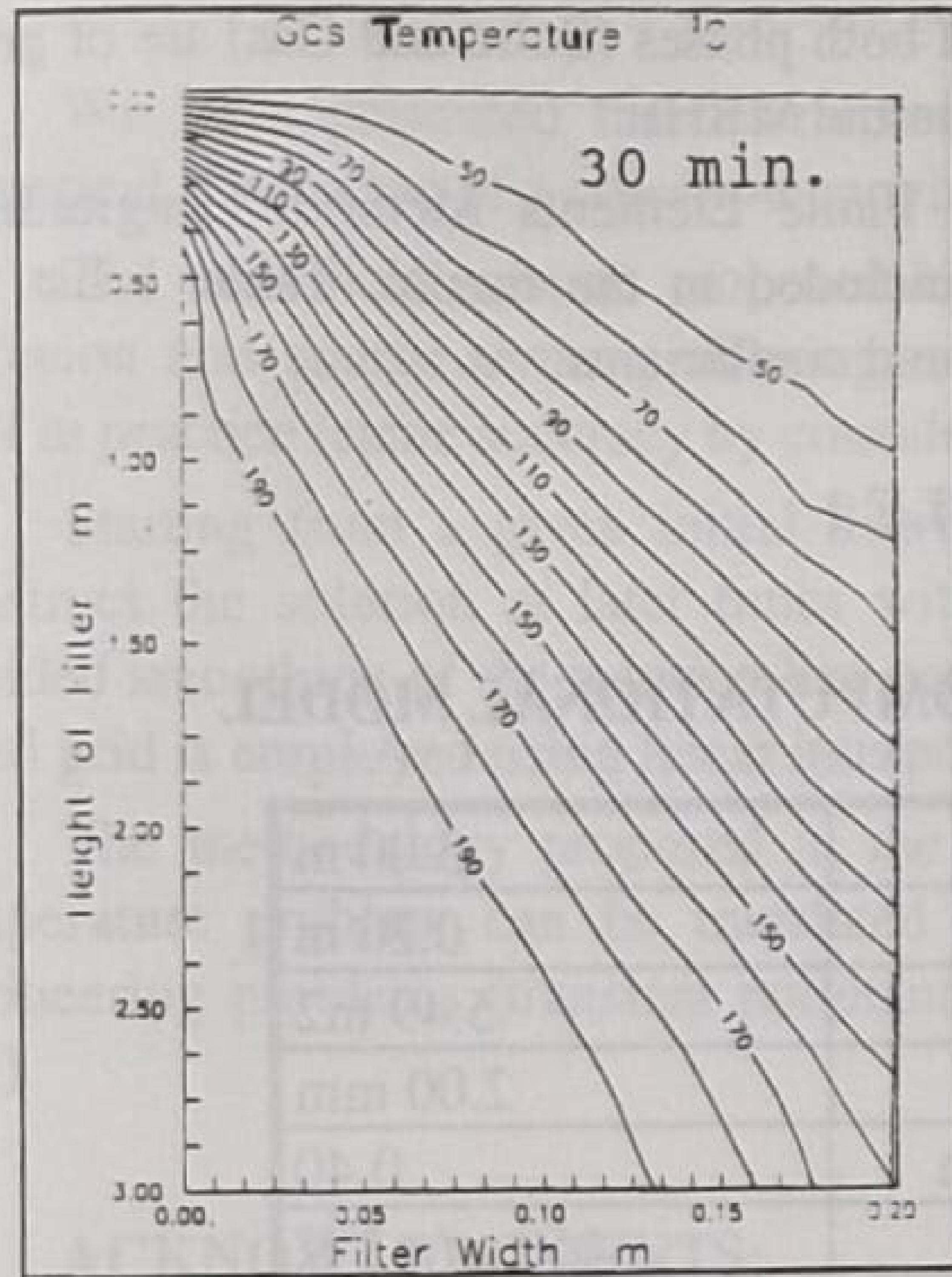


Fig. 5: Gas temperature distribution in the MBHE for t = 30 min.

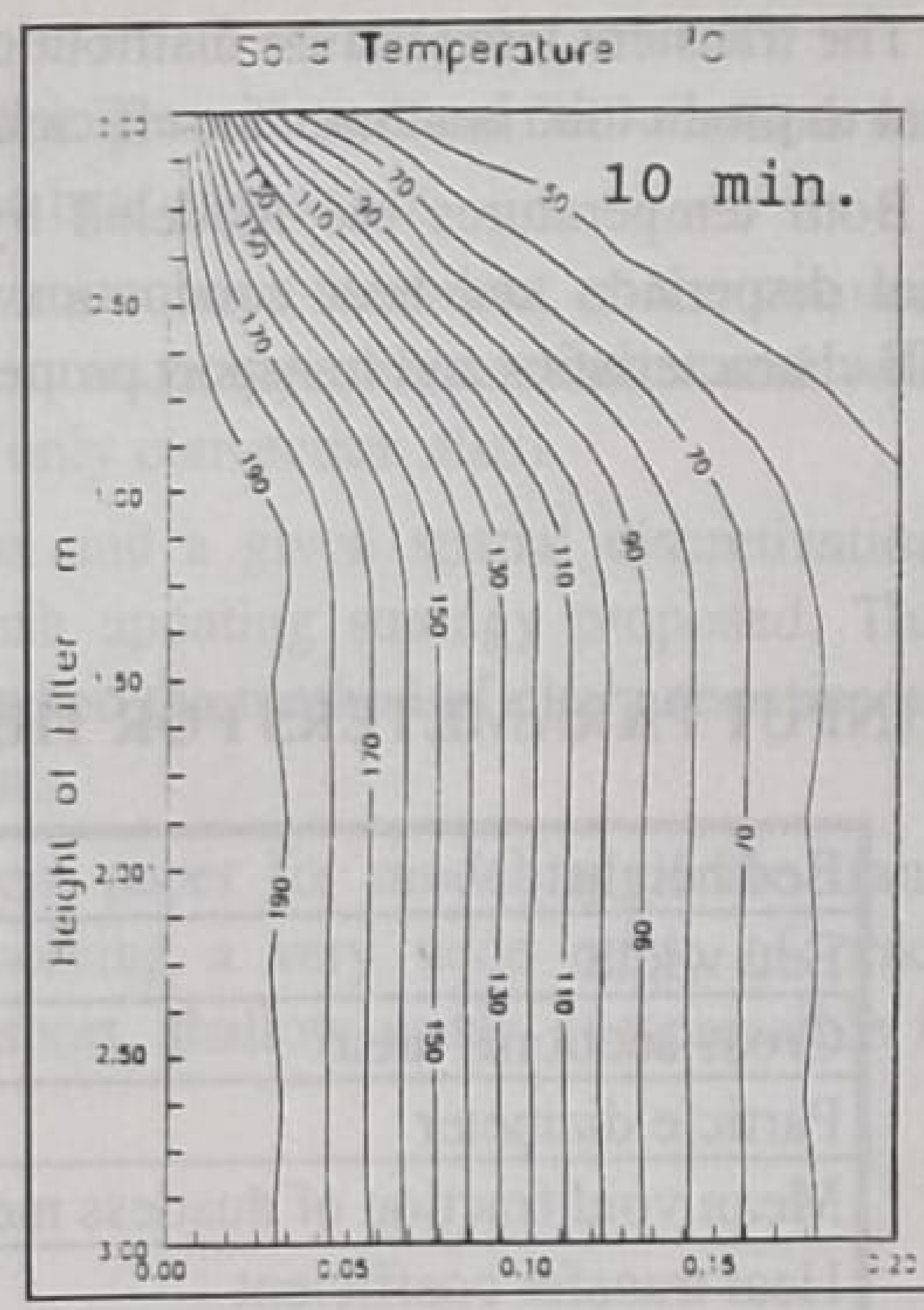


Fig. 6: Solid temperature distribution in the MBHE for t = 10 min.

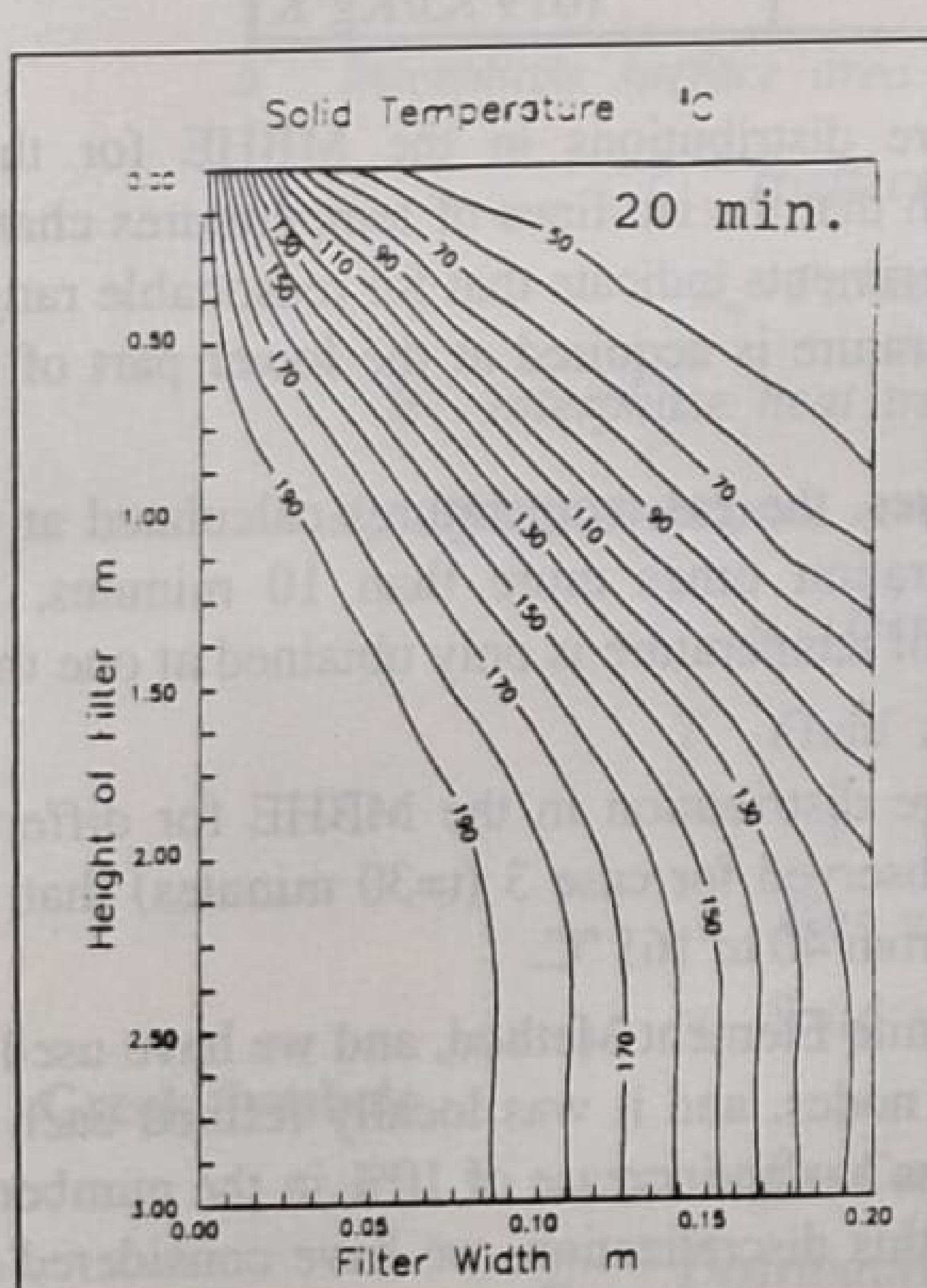


Fig. 7: Solid temperature distribution in the MBHE for t = 20 min.

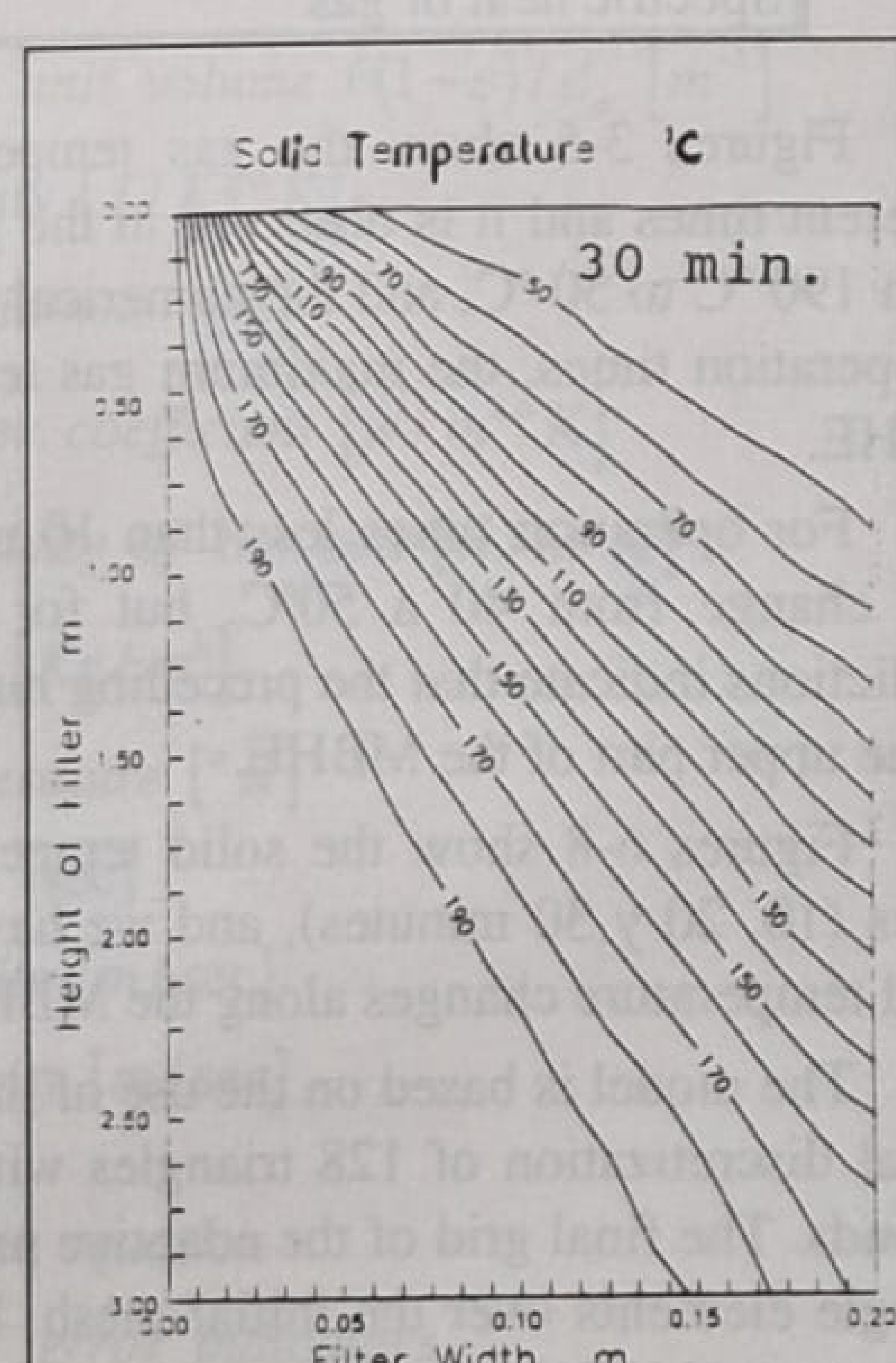


Fig. 8: Solid temperature distribution in the MBHE for t = 30 min.

The transient temperature distributions of both phases (Solid and Gas) are of great interest to predict the heat transfer efficiencies in the MBHE.

Both temperatures are modeled by the Finite Elements Method. Longitudinal thermal dispersion and heat conduction are included in the model. Table 1 list the MBHE characteristics and transport properties and coefficients.

TABLE 1

INPUT PARAMETERS FOR THE COMPUTATIONAL MODEL

Bed height	3.00 m
Bed width	0.20 m
Cross-sectional area	5.49 m2
Particle diameter	2.00 mm
Mean void fraction of dustless medium	0,40
Heat transfer coefficient	150 w/m2°K
Solid velocity	0.166 cm/sec
Gas velocity	0.50 m/sec
Solid density	2500 Kg/m3
Gas density	0.745 Kg/m3
Specific heat of solid	670 KJ/Kg°K
Specific heat of gas	1019 KJ/Kg°K

Figures 3-5 show the gas temperature distributions in the MBHE for three different times and it is observed in the graph that the iso-lines of temperatures change from 190 °C to 50 °C, and the numerical experiments indicate that for reasonable ranges of operation times, the maximum gas temperature is acquired at the lower part of the MBHE.

For operation times less than 10 minutes, the gas temperatures calculated at the exit change from 40 a 50°C, but for operation times more than 10 minutes, the predictions indicate that the preceding range of temperature is only obtained at one third of the upper part of the MBHE.

Figures 6-8 show the solid temperature distribution in the MBHE for different times (10, 20 y 30 minutes), and we have observed for case 3 (t=30 minutes) that the solid temperature changes along the MBHE from 40 to 161 °C.

The model is based on the use of the Finite Element Method, and we have used an initial discretization of 128 triangles with 3 nodes, and it was locally refined each 30 seconds. The final grid of the adaptive process has an increase of 10% in the number of triangle elements over the initial mesh. For this discretization, we have considered for time steps of 10E-2 seconds.

The temperature distribution for gas and solid was determined for different operation times (10, 20 and 30 minutes) using the Finite Element Method with Adaptive Strategy

CONCLUDING REMARKS:

We have presented the development of a general and unified method for the numerical simulation of a crossflow moving bed heat exchanger.

The numerical scheme proposed leads to a correct treatment of the convection, diffusion and source terms producing excellent accuracy characteristics and working well in practice (same accuracy by considering only convection also).

Starting from a given initial distribution and a given spatial discretization we construct the solution at later times with mesh updating strategy proposed. Thus is avoided smoothing of the solution like occurs when the method of characteristics with a fixed grid is employed using linear interpolation.

The methodology proposed in the present paper for modeling of the transient temperature problem can be translated for solving a very wide range of practical engineering problems (transient pollutant transport, shallow water, compressible flow, etc.).

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NOMENCLATURE

a *Interphase surface area per unit volume* $6(1-\varepsilon)/d_m\ [m^{-1}]$

c *Heat capacity* $[J/Kg^{\circ}K]$

d_m *Particle diameter* $[m]$

h *Interphase heat transfer coefficient* $[w/m^2{}^{\circ}K]$

K_e *Effective thermal conductivity of the bed* $[w/m^{\circ}K]$

p *Density* $[Kg/m^3]$

T *Fluid temterature* $[^{\circ}K]$

t *Time* $[\sec]$

u *Gas velocity* $[m/\sec]$

v *Solid velocity* $[m/\sec]$

Greek Symbols

α,β *Const. in equation*

Σ_i *Distribution of error indicators*

θ *Solid temperature*

ε *void fraction*

Subscripts

f *Fluid*

0 *Initial*

s *Solid*

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