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ANALYSIS OF THE ELFUEL COAL DRYING FACILITY

by

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I. INTRODUCTION

The ELFUEL coal drying facility is designed to utilize the high heat transfer characteristics of a moving packed bed counter–current heat exchanger to efficiently "hot–water dry" lignite coal. Past research into hot water drying of lignite indicates the process is energy inefficient, requiring greater energy input than what can be extracted from the treated lignite. The novel approach of the ELFUEL coal drying facility utilizes the high heat transfer characteristics of a counter–current solid/liquid packed bed to efficiently add and later remove heat to and from descending coal in a pressurized cylindrical vessel. This approach uses raw coal continuously descending in a vertical cylindrical refractory. Coal, upon entering the refractory at the top, gradually heats to process temperatures near the location of hot water injection through contact with hot water flowing upward. Below the point of hot water injection, cool water is forced upward past the descending coal to trap or conserve heat or energy in the system. Sufficient energy is conserved by this design to economically hot–water dry lignite coal.

Design of a counter–current energy efficient system which adds and then removes heat has not been reported in the literature. Wonchala and Wynnyckyj (1986) reports counter–current packed bed processes are common in the metallurgical industries. Some important example include the iron blast furnace and iron–ore pelletizing shaft furnace which are very useful since they exhibit a very high potential heat transfer efficiency. However, the metallurgical counter–current gas–solid heat exchangers have not been found to be energy efficient due to channeling of hot gases (Wonchala and Wynnyckyj, 1986).

It was the purpose of this study to determine whether the ELFUEL coal drying facility outlined in Minnesota Power's proposal "ELFUEL Demonstration of Low–Rank Coals" to the U. S. Department of Energy, Clean Coal Technology, Round #3 will perform as described and meet the objectives of the process, the economical hot–water drying of lignite coal.

II. GENERAL DESCRIPTION OF THE ELFUEL LUMP COAL DRYER

The ELFUEL coal dryer facility is a counter current solid–liquid heat exchanger. Basic features of this exchanger, shown in Fig. 1, include a cylindrical refractory designed to withstand pressures sufficient to maintain water at its saturated liquid state, a lock hopper arrangement, that feeds the lignite coal into the refractory, a conveyor system to remove the material out of the bottom of the refractory, and various ports for the introduction of process heating and cooling water.

According to the patent application, and information from Minnesota Power, the reactor vessel is circular with an inside diameter of 2.74 meters (9 feet) and a height of 33.5 meters (10 feet). The design feed rate is 60 tons per hour of lignite with a particle top size of 7.62 cm (3 in.). Raw coal at 295 K (72°F) is added and distributed in the top 4.6 meters of the dryer, packing the refractory with coal. The active region of the reactor vessel consists of two intermediate zones designed to first, heat the coal to process temperature (preheating and reaction zone) and second, remove this heat within the refractory. In the upper 3/4 of the preheating and reaction zone, the first 9.4 meters, coal slowly descends due to the continuous removal of coal at the bottom of the dryer, and is heated by the rising water. Sufficient transfer of energy must occur to allow the temperature of the coal to reach approximately 573 K (572°F) at the point of hot water injection, or the bottom of the reaction zone. According to the information given in the patent application, approximately 8 tons/hr of hot water 600 K (625°F) will supply sufficient heat to meet this requirement, and 24 tons/hr of cold water at 311 K (100°F) added at the bottom will be necessary to capture the heat being drawn downward by the coal. This cooling process will occur in the last 1/4 of the reactor vessel, the cooling zone of 6.5m. The overall process should trap sufficient heat in the reactor vessel to result in an economical means of hot–water drying coal.

III. ANALYSIS

A. General

To determine whether the ELFUEL coal dryer facility will perform as outlined in the Minnesota Power Patent application, two mathematical models were developed. These models describe the motion and heat transfer characteristics of the solid–liquid heat exchanger found in the preheating and reaction zone and the cooling zone of the dryer. The first model analytically describes the heat transfer characteristics of a counter current solid–liquid heat exchanger, assuming uniform water velocity and uniform coal velocity. It results in the temperature distributions of the coal and water in the solid–liquid heat exchanger for a given incoming coal and water temperature. The second model is a two–dimensional computational fluid flow model developed to describe the water flow and heat transfer characteristics of the coal and water. The model assumes a uniform coal velocity due to the packing of the coal. Of particular interest is the tendency to have natural convection occur within the packed coal which could increase the heat input that the process requires. These models and the physical properties of the materials in the dryer are described in this section. Finally, the fluidization velocity of the coal particles in water is analyzed and compared to the water flow velocities present. The purpose of this is to determine whether significant amounts of coal will be picked up and carried upward by the water flow. Coal fluidization would greatly complicate the analysis and could result in an increase in required heat input.

B. Lignite Coal Physical Properties

1. Background

The general physical properties of the lignite coal which are important to the fluid motion and heat transfer characteristics of the reactor vessel include coal density, water density, porosity, thermal conductivity, and specific heat. Values typical of lignite coal are summarized in Table I. All of the parameters listed in Table I are relatively weak functions of temperature. As an approximation at this stage of the coal dryer design, however, the values listed will be used.

Table I – Material Properties

Property	Value	Source
Water density @ 500 K	980 kg/m^3	Incropera et al., 1985
Coef. of Vol. expansion	0.001 K^{-1}	Incropera et al., 1985
Coal density	1400 kg/m^3	Nehls, 1989
Water specific heat	4500 J/kg K	Incropera et al. 1985
Coal specific heat	.33 BTU/lb°F 1381 J/kg K	Nehls, 1989
Coal Conductivity	.26 W/m K	Merrick, 1977
Shape factor (ϕ_s)	.60	Kunii et al., 1969
Water conductivity @ 400 K	.688 W/m K	Incropera et al., 1985

Other physical properties which need to be defined for model development include the viscosity of the lignite coal mixture, the lignite coal porosity, surface area for heat transfer, convective heat transfer coefficient of water to coal, and since this is a drying process, the mass loss of water from the lignite coal as a result of hot–water drying. These five parameters will be described in the following sections.

2. Slurry Viscosity

A coal water mixture has been reported by others (see Cheremisisnoff and Gupta, 1983) to behave like a bingham plastic. A bingham plastic behaves as an elastic solid below some limiting shear stress, but as a viscous fluid (Newtonian) above it. The University of North Dakota, Energy and Environmental Research Center (EERC) has reported a reduction of viscosity with temperature for a coal slurry (Potas, 1990), However, little has been reported regarding the shear stress versus shear rate for a coal slurry as a function of temperature. To address this question, the EERC was subcontracted to investigate the rheology of an approximately 40 wt% dry solids solution of BNI Lignite coal using their Haake D100/300 high temperature rheology system. The BNI lignite mixture that was tested, due to instrument limitations, did not cover the full range of particle sizes up to 3 inch maximum, but consisted primarily of fines. The viscosity data reported represented a 38.1 wt% dry solids mixture of fines to be found in the Coal Dryer facility. Kunii and Levenspiel (1969) report this to be an appropriate approximation. The fines tend to act as a lubricant, reduce the friction of the coarse material, and the coarse material does not significantly influence viscosity. The viscosity data collected should therefore represent actual process conditions.

The results from the EERC's coal water viscosity study are shown in Fig. 2. This figure indicates only a slight bingham fluid behavior, especially considering that the viscosity measurements below a shear rate of under 100 sec^{-1} are not reliable (Potas, 1990). In addition, there appears to be only a slight decrease in viscosity with temperature past 100°C. Thus, modeling this system with a constant apparent viscosity of 60 cP (.06 Kg/ms) should represent the viscosity to be anticipated in the reactor vessel fairly well.

3. Particle Size Distribution

A sieve analysis was carried out on samples of coal supplied by EERC. The analysis was performed in accordance with ASTM Designation: D4749-87, "Standard Test Method for Performing the Sieve Analysis of Coal and Designating Coal Size." The results are shown in Fig. 3. The median particle size by weight (D_{50}) is approximately 2.8 mm.

4. Lignite Porosity

The porosity of coal sample is the ratio of the volume of voids to the total volume of water and coal. The volume of voids may be influenced by many different aspects of the coal particle, such as the volume of micro pores. The pores for water passage were primarily of interest to this study. The volume of these pores was estimated by the following method. A moist sample of BNI Coal was dropped into a 1 liter graduated cylinder, similar to how the coal will be placed in the coal dryer. A measured volume of water was added until the water level and the apparent solids level agreed. This should be representative of the volume of voids of the material which would be found near the top of the reactor vessel. The porosity representing this condition was roughly 43 percent. This sample was then tamped with a metal rod, which would represent the compaction due to the weight of the coal in the reactor. This tamping reduced the porosity to approximately 28 percent. Considering these findings, a reasonable estimate of porosity in the Coal Dryer facility for the preliminary design stage was taken as 30 percent.

5. Heat Transfer Characteristics of a Bed of Particles

The heat transfer from water flowing through a packed bed of uniform coal particles can be described by:

$$Q = hA_s\,(T^w - T^c) \tag{1}$$

where

h = convective heat transfer coefficient (W/m^2K)
T^c = temperature of the coal particles (K)
T^w = temperature of the water (K)
A_s = surface area for heat transfer (m^2), and
Q = heat transfer (W)

According to Incropera et al. (1989) the heat transfer coefficient for a bed of particles can be estimated using the following equation:

$$h = 2.06\,\rho u\, c_{p_w}\,\frac{\phi_s}{\epsilon}\,Re^{-0.58}\,Pr^{-0.67} \tag{2}$$

ϵ = porosity of packed bed
ϕ_s = shape factor (0.6 for liguite)
ρ = density of fluid (kg/m^3)
u = flow velocity of fluid past the particle (in this case $u_c + u_w$)
Pr = Prandtl number = $c_{p_w}\mu/k$
k = thermal conductivity of the fluid (W/m K)
μ = viscosity of the mixture
c_{p_c} = specific heat of the lignite (J/kg K)
Re = particle Reynolds number = $\rho\, uD_p/\mu$
u_c = cross-sectional average velocity of coal (m/s)
u_w = cross-sectional average velocity of water (m/s)
D_p = particle diameter (m)

Assuming D_{50} is representative of the particle diameter, D_p (2.8 mm from Fig. 3), a convective heat transfer coefficient of approximately 3000 W/m^2K results. As this value appeared very large, a check was performed using a relationship given in Holman (1981) to estimate the heat transfer coefficient for flow of liquid past a sphere with the same diameter. The heat transfer coefficient determined for a sphere was very similar.

The other factor in Equation 1 which governs heat transfer is the surface area, A_s. For a packed bed of uniform spherical particles, the surface area is:

$$\frac{A_s}{\forall} = \frac{6(1-\epsilon)}{D_p} \tag{3}$$

where

A_s = surface area of particle (m^2)
$\forall$ = volume of sample (m^3)
ϵ = porosity
D_p = diameter of particle (m)

This surface area will be used herein and should give a conservative estimate of the heat transfer between coal and water in the hot–water drying process.

6. Mass Loss of Coal

Coal drying implies a loss of water during the ELFUEL process. This is not entirely correct. According to a recent study performed by the University of North Dakota EERC for BNI Coal and DOE (Potas et al., 1990), the coal coming out had the same moisture content as when it entered, during the process of hot–water drying. Lignite coal appears to lose mass, primarily by driving off gaseous CO_2 and organic and inorganic compounds from the pores of the coal (patent application). The counter–current flow of water past the particle sweeps these compounds upward. Drying of the coal particle is an outcome of the processes' ability to change the behavior of the coal particle from a hydrophillic to a hydrophobic compound (Potas, 1990). Hydrophic compounds possess no affinity for water, and the water can be removed easily from the coal by oil agglomeration, the second phase of the drying process that is not considered in this study.

For modeling purposes, the coal does not have the density of the coal particle, but of the coal plus the weight of water in the micro pores and on surface of the particle, or the moisture content of the lignite. The EERC (Potas, 1990), reports this moisture content to be 34%, with a total mass loss of 20%. No indication of volume change is given. The mass loss will not be modeled at this point. However, the density will be adjusted to account for the water in the pores. Accounting for moisture content, this leads to a wet lignite coal density and specific heat of approximately 1256 kg/m^3 and 2217 J/kg K, respectively. These latter values more correctly describe the wet coal input and output of the ELFUEL coal dryer, and will be used herein to represent the lignite coal.

C. One–Dimensional Heat Transfer Modeling of the Coal Dryer

Consider the counter current solid–liquid heat exchanger shown in Fig. 4. This represents the region from the point of hot water injection to the input of coal at the top of the dryer. It also could represent the region from the point of hot water injection (assuming a coal temperature) to the point of cooling water injection in the cooling zone. The heat balance equations for water temperature, T^w, and coal temperature T^c are:

$$\frac{dT^w}{dz} = K^w\,(T^w - T^c) \tag{4}$$

$$\frac{dT^c}{dz} = K^c\,(T^w - T^c) \tag{5}$$

where

$$K^w = \left[\, h\,\frac{6(1-\epsilon)}{D_p}\,\right]\left[\,\frac{1}{\rho_w\;u_w\;c_{p_w}}\,\right] \tag{6}$$

$$K^c = \left[\, h\,\frac{6(1-\epsilon)}{D_p}\,\right]\left[\,\frac{1}{\rho_c\;u_c\;c_{p_c}}\,\right] \tag{7}$$

where

z = vertical distance laong the heat exchanger
D_p = coal particle diameter,
ϵ = coal porosity
ρ = density (subscript w for water and c for coal)
u = velocity (subscript w for water and c for coal), and
c_p = heat capacity (subscript w for water and c for coal).

Then,

$$T^c(z) = \frac{K^c}{\delta}\,\Delta T' e^{\delta z} + T_{IN}^{c} - \frac{K^c}{\delta}\,\Delta T' \tag{8}$$

$$T^w(z) = \frac{K^w}{\delta}\,\Delta T' e^{\delta z} + T_{IN}^{w} - \frac{K^w\,e^{\delta L}}{\delta}\,\Delta T' \tag{9}$$

Here

$$\Delta T' = \frac{T_{IN}^{w} - T_{IN}^{c}}{\frac{K^w}{\delta}\;e^{\delta L} - \frac{K^c}{\delta}} \tag{10}$$

where

$\delta = K^w - K^c$

T^w_{IN} =temperature of water at the point of heating (or hot–water injection)

T^c_{IN} = temperature of coal (k) flowing into the reactor.

L = length of the heating (or cooling) zone.

These equations may also be used to describe the cooling zone below hot–water injection if T_{IN}^c = coal temperature after hot–water injection and T_{IN}^w = water temperature coming into the bottom of the heat exchanger.

For the special cases when $\delta = 0.0$ ($K^w = K^c$)

$$\frac{T^c(z) - T^c_{IN}}{T^w_{IN} - T^c_{IN}} = z/L \tag{11}$$

and

$$\frac{T^w(z) - T^w_{IN}}{T^w_{IN} - T^c_{IN}} = \frac{z}{L} - 1 \tag{12}$$

Given the coal and water inputs described in Section II, the temperature profile predicted with Eqs. 8 and 9 is shown in Figure 5. Due to the large heat transfer coefficient of the packed bed, the coal temperature and water temperature are almost equivalent.

The profile shown in Fig. 5 has a large temperature gradient near the top and bottom of the vessel. This is not desirable since such a large temperature gradient would be sensitive to any unsteady perturbation in the flow field, such as a pressure pulse, short circuiting, natural convective currents and the efflux of liquids from the coal particles. Such perturbations could destroy the temperature gradient, and significantly decrease the efficiency of the hot–water drying process. The reason that such a large temperature gradient is possible is the large heat transfer between the coal and the water, relative to the slow flow–through velocities. The primary task, therefore, is to decrease the temperature gradient so that it is not sensitive to perturbations in the flow field.

A linear temperature gradient is the special case described above when $\delta = 0$ or K^c is equivalent to K^w. Assuming h and ϵ are constant, this requires the heat flux term of the coal $\rho_c u_c c_{p_c}$ to be equivalent to the heat flux term of the water $\rho_w u_w c_{p_w}$. Fixing the coal input at 60 tph, a water discharge of 29.56 tph would be required for the given specific heats to achieve this linear profile, an 8 percent reduction in total water required. The temperature profile which would exist under this condition is shown in

Fig. 6. Using IR heating the temperature profile shown in Figure 7 should result because it is possible to make $\delta=0$ both above and below the heating element. Comparison of IR and hot–water heat, however, is a topic for further study, discussed in Section V.

The sensitivity of the linear temperature profile was tested through the use of a one–dimensional unsteady computer model, similar to the analytical model except with an unsteady term incorporated. The model demonstrated that the time required to change from one steady state profile to another, i.e. from the results in Fig. 6 to those in Fig. 5, would be great, due to the large heat capacities of the coal and water and the slow flow–through velocities. Thus, if care is taken in setting up an initial temperature profile, the results of the model indicate that it should be possible to maintain that profile through real–time control of the system. It is likely, that with proper system monitoring and control, the hot–water dryer could operate with the temperature profile given in Fig. 7 for either IR heating or hot–water heating.

D. Two–Dimensional Computational Fluid Dynamic Model of the Coal Dryer

1. Objective

The one–dimensional modeling resulted in the temperature profile as shown in Figure 6, a large linear inverse temperature profile (cold above hot) existing in the upper regions of the reactor vessel. This may be an unstable situation because of the potential for free convection or motion due to a density inversion. The density inversion would tend to induce a downward motion, counter to the required upward vertical motion of the fluid. Free convective cells that would occur in a cylindrical reactor 3 m in diameter would be approximately 1.5 m in size, and could induce short circuiting due to the higher velocities. Thus, free convection could cause the process to lose its energy conservation features, and the economic advantages of the hot–water drying process would be reduced. To address this concern, a two–dimensional computational fluid dynamics model of the upper zone of the reactor vessel was developed. A description of the assumptions used, the fluid–solid conservation equations of motion, the numerical algorithm to solve this system of partial differential equations and results are presented in this section.

2. Assumptions

The two–dimensional computational model describes the fluid flow and heat transfer characteristics of the preheating and reaction zone, shown in Figure 1. It represents the first 19.4 m described by the analytical model of Section III.C or the region of temperature and density inversion. The initial temperature profile will be assumed to be linear since the one–dimensional unsteady computational model indicated that it will be possible to set up this profile with proper process control.

Assumptions similar to the one–dimensional analysis were made: constant heat capacities, adiabatic reactor walls, minor particle–to–particle conduction, and negligible radiative heat transfer. The buoyant forces were modelled using the standard Boussenesq approximation and a constant coefficient of volumetric expansion (Turner, 1973). The frictional resistance of the coal particles was modeled using the Ergun equation (Kunii and Levenspiel, 1969), with a shape factor, ϕ_s, to account for the non–spherical shape of the particles as presented in Section III.B.1. Finally, the coal particles are assumed to be isothermal, a reasonable assumption in these initial computations considering the very large heat transfer coefficient presented in Section III.B.6.

Another item of concern was the longitudinal dispersion of heat. An estimate of the longitudinal dispersion coefficient was made for the porous media. The coefficient of hydrodynamic dispersion has been found to be a function of the Peclet number of molecular diffusion (Bear, 1972). The Peclet number is defined as

$$Pe = \frac{uD_p}{D_m} \tag{13}$$

where

u = velocity
Dp = particle diameter
Dm = molecular diffusion coefficient

The value of Dm for water had been given by Bear (1972) as $5\text{x}10^{-10}$ m^2/s. When V = $1.4\text{x}10^{-3}$ m/s and Dp = 0.0025 m, the Peclet number is calculated to be about 7000. Using the relations given in Bear, the ratio of the longitudinal–to–molecular diffusion coefficients is about 10,000. Therefore, the longitudinal dispersion coefficient is about $5\text{x}10^{-6}$ m^2/s. This approximate value was used in the numerical calculations to estimate the significance or sensitivity of the system to the longitudinal dispersion of heat, which was found to be insignificant under the temperature regimes modeled.

3. Solution Algorithm

The governing conservation equations for the two–phase mixture follow those of Beckermann et al. (1986a, b). The dependent variables of the model are the axial velocity, $u^w(x,r) = u$, and the radial velocity $v^w(x,r) = v$ of the water, the temperature of the coal $T^c(x,r)$ and water $T^w(x,r)$ and the pressure P(x,r). The independent variables are the radial and axial distances, r and x.

To account for the interfacial friction due to the packed bed, the Ergun equation is included in the momentum equations. The Ergun equation is given by

$$\frac{\partial P}{\partial z} = \left[\frac{150\mu(1-\epsilon^2)}{(\phi_s D_p)^2\, \epsilon^3} + \frac{1.75\rho_w(1-\epsilon)}{\phi_s\, D_p\, \epsilon^3}\, |u| \right] u \tag{14}$$

and describes the pressure drop across a porous layer (Kunii and Levenspiel, 1969). The first term in this equation represents viscous resistance and the second term represents inertial resistance, or the loss of pressure due to form drag on the coal particles. Combining the Ergun equation, the Boussenesq approximation, and conservation of mass and heat results in conservations equations describing the heat transfer and fluid motion in the ELFUEL coal dryer facility. The equations are given in the Appendix.

Boundary conditions of the two–dimensional model are similar to the one dimensional description with the incoming water and coal temperature and velocity distributed uniformly across the domain at opposite ends of the domain. In addition, due to the slug flow nature of the descending coal, the coal velocity is assumed to be uniform and constant throughout the domain. Buoyancy effects or free convection should become evident through a nonzero radial component of velocity, from the resulting stream function of the flow, and from temperature variations across the width of the vessel.

The solution of the system of partial differential equations given in the Appendix is performed using the DSIMPLER (Brent, 1989a, b) computer program. DSIMPLER is a general purpose code for elliptic, transient two–dimensional heat transfer and fluid flow calculations. DSIMPLER uses the control–volume based numerical scheme described in Patankar (1980) and used successfully world–wide to solve many types of transport problems.

The calculation domain is discretized by dividing it into a number of control volumes, and the conservation equations are then numerically integrated over the domain. The main control volumes are used for the representation of temperature and pressure, and velocity control volumes are offset by a half–control volume from the main control volumes. The upwind type of staggering is used to resolve the pressure–momentum coupling (see Patankar, 1980 for further description). To investigate free convection in the ELFUEL coal dryer, a 10 by 20 grid size was used to represent the upper portions of the coal dryer facility.

4. Model Verification and Results

The model was first verified by neglecting the buoyancy term and comparing the results with the analytical solution. Model comparison to the analytical solution is shown in Figure 8 and compares favorably. Only slight discrepancies are noted, a consequence of the discretization used to model the input and output boundary conditions.

Adding buoyancy forces to the model results in an identical answer, i.e. no natural convection cells occur. Convective motion was achieved by artificially increasing the coefficient of volumetric expansion β by two orders of magnitude. This, of course, is not realistic because we have a fairly good representation of all the terms in the computer model. Increasing β has the same effect as increasing the temperature gradient. Thus, $\partial T/\partial z$ would have to be increased by a similar percentage in order to have convective motion occur in the ELFUEL coal hot–water drying process. Performing an order of magnitude analysis of the z–direction equation of motion yields the reason for this result.

Since the velocity is uniform in the z and r direction in the 2–D computational solution, the derivatives in these directions are zero. This reduces the z–direction momentum equation (Eq. A2 and A3) to

$$\frac{\partial P}{\partial z} = - \rho_{ref} \, \beta(T - T_{ref}) - \left[\frac{150\mu(1-\epsilon)^2}{(\phi_s D_p)^2 \epsilon^3} + \frac{1.75\rho(1-\epsilon)}{\phi_s D_p \ \epsilon^3} |u| \right] (u-u_c) \tag{15}$$

which describes the pressure gradient in the z–direction. For buoyancy to dominate the buoyant term should be greater than the pressure loss terms in the Ergun equation or

$$\begin{aligned} -\rho_{ref}\, g\beta(T - T_{ref}) > {} & \left[\frac{150\mu(1-\epsilon)^2}{(\phi_s D_p)^2\epsilon^3}\right. \\ & \left. + \frac{1.75\rho(1-\epsilon)}{\phi_s D_p\ \epsilon^3}\ |u|\right](u - u_c) \end{aligned} \tag{16}$$

To obtain this result, beta must increase from 0.001 to 0.04, an increase of approximately 40 times. This could also be accomplished by increasing the D_{50} particle diameter from 2.8 mm to 20 mm. This is a considerable increase, indicating that the fine coal particles are critical to the stability of the dryer operation. With the fine coal particles, any gravitational acceleration due to buoyancy will be offset by the inertial and viscous resistance of the porous media and no apparent motion will occur. In other words, natural convection will not occur in the ELFUEL hot–water drying process because of the extremely large head loss that occurs in the porous media, driving the flow in one direction and suppressing any natural convection cells.

Equation 16 also gives a convenient expression to describe the pressure gradient required in the EL FUEL system to drive the fluid through the porous media. As presented above, the pressure required will be approximately 124,000 $N/m^2/m$ or 5.5 psi/ft, minor as compared to the pressure required to maintain water in its liquid state at 600 K.

The longitudinal dispersion of heat can become a significant factor if the temperature gradient is highly nonlinear. With the preliminary design modifications proposed herein, the temperature gradient of the ELFUEL hot–water dryer was linear. Thus, there was no net longitudinal dispersion of heat in the dryer.

D. Fluidization Velocities for Coal Particles

The final possibility investigated was the fluidization of coal particles by the water flow, such that the particles move upward with the water instead of downward. Of current interest is the minimum fluidization velocity. The onset of fluidization occurs when the drag force on the particle by the moving fluid is equal to the weight of the particles. An expression for this velocity, u_m, is given by Kunii and Levenspiel (1969) as

$$u_m = \frac{(\phi_s D_p)^2 (\rho_c - \rho_w)}{150\mu} \, g \left[\frac{\epsilon^3}{1-\epsilon} \right] \tag{17}$$

using the previously defined notation. With $D_p = 0.0025$ m, $\epsilon = 0.3$, and using the viscosity of water, μ, as 1.74×10^{-4} kg/ms. the minimum velocity is computed to be about 0.014 m/sec. The superficial velocity for the reactor with a water flow of about 30 tph is about 0.0014 m/sec or about a factor of 10 lower. This appears to be a safe margin against fluidization of the entire bed. It should be noted, however, that the velocity is dependent on the square of the particle diameter. Therefore, particle sizes of a diameter less than 0.8 mm may be fluidized by the flowing water. Figure 3 indicates that these particles account for approximately 17 percent of the coal by weight. Thus at this time, it appears that extensive fluidization of the ELFUEL reactor will not occur.

IV. CONCLUSIONS

The ELFUEL hot–water drying reactor is unstable under certain operating conditions, in that it will not maintain the required temperature inversion. The rector operation can be made stable by setting the coal and water mass fluxes equal, setting up an initial linear temperature profile, and proper control during operation. More specific conclusions follow:

1. Reduction of the cooling water input into the reactor by 8 percent resulted in a linear temperature profile for the ELFUEL hot–water drying process.
2. Unsteady one–dimensional computer modeling of the process indicates that, once the linear temperature profile is established, the time required to change to another steady state temperature profile was great. Therefore, it is likely with proper system monitoring and control that the ELFUEL hot–water drying process could maintain a linear temperature profile.
3. With hot–water heating, the linear temperature profile is only possible above the location of heat input, under currently proposed operation. With IR heating, a linear temperature profile is possible throughout the reactor because no fluid is added and the mass fluxes up and down remain constant. An active proper process control should result in a linear temperature profile for both hot–water heat and IR heating.
4. The two–dimensional computational fluid dynamic model of the ELFUEL dryer indicates that no natural convection would occur within the porous media (coal). The reason is shown to be the large headloss that occurs in water flow through the coal mixture, which directly counteracts buoyancy forces. For natural convection to occur, the temperature gradient in the reactor would need to be approximately 40 times greater than that of a linear temperature profile.
5. A linear temperature profile also results from the two–dimensional computational fluid dynamic model because natural convection would not occur in this initial examination of the process.
6. There is no net heat flux from longitudinal dispersion in the porous media with a linear temperature gradient. Thus, longitudinal dispersion would not influence a linear temperature gradient except to help stabilize it, since any dispersive heat flux would move back toward a linear temperature gradient.
7. It appears that extensive fluidization of the ELFUEL coal particles will not occur. Particles of a diameter less than 0.8 mm may be fluidized by the flowing water. These particles account for approximately 17 percent of the 3x0 coal by weight.

V. RECOMMENDATIONS FOR FURTHER STUDY

There are a number of issues that need to be addressed before completion of the final pilot plant design. These are divided into two general categories:

A. Further Simulations with the Two–Dimensional Fluid Dynamic Computational Model

The computational model has been set up for this reactor simulation and verified through comparison with the one–dimensional analytical model. Further computer simulation, instituting additional aspects of the process, is advised. These additional aspects include the following:

1. In the preliminary investigation, the reactor walls were assumed to be adiabatic. The effect of non–adiabatic walls upon the temperature profiles and the velocities within the reactor needs to be incorporated. These simulations would provide advice on the insulation required to have the process function properly, and the heat loss through such insulation. It would also enable a total energy balance on the system.
2. Institute time dependent, two–dimensional simulations to investigate the unsteady character of the temperature profile more fully. This is required for the remainder of the simulations to answer the many questions that may occur about the ability of process engineers to maintain a linear temperature profile in the reactor.
3. The median (by weight) particle diameter of 2.8 mm was used throughout this study. A distribution of coal particles similar to that of the 3x0 coal should be used in the heat transfer and flow computations to more accurately simulate the medium. Partial fluidization and coal temperature could then be simulated.
4. Incorporate fluidization into the model. Approximately 17 percent of the coal particles may be fluidized. The impact of this on process control should be incorporated.
5. Incorporate the mass loss of CO_2 and other compounds that will occur in the process and the heat loss that occurs.
6. Investigate the impact of the nonuniform bed packing that surely will occur.
7. Investigate the impact of nonuniform heating of the water and the coal through the hot–water injection system and through the IR heating.

8. Investigate the various means of setting up an initial linear profile in the reactor. One suggestion is to set up ports at various heights on the reactor walls where hot water of the required temperature can be injected or withdrawn. Then the initial temperature profile would be a number of steps from 600°K to 293°K as one moves up the reactor from the heat input location, and vice versa as one moves down from that location.

9. Investigate the control sequence required to maintain a linear temperature profile. The ports described under item 6 could also be used for real time process control. The ramification of various control operations could be investigated, and control operation could be optimized through such computational simulations.

10. Further preliminary design of the reactor diameter, height, water and coal inputs, etc. could also be accomplished with this simulation model.

B. A reduced scale (approximately 1/2) model of the upper 20% of the reactor should be built to:

1. Experimentally determine the fluidization that could occur in the reactor.

2. Verify the computational model simulations for startup and operation of the ELFUEL process.

3. Test and modify process monitoring and the optimized control sequence in real life situations to determine the best operational mode for plant personnel.

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APPENDIX

Conservation equations for the two–dimensional fluid dynamic computation model of the ELFUEL coal drying facility.

The conservation equations used in the two–dimensional fluid dynamic computational model are as follows:

Continuity

$$\frac{\partial u}{\partial z} + \frac{\partial v}{\partial r} + \frac{v}{r} = 0 \tag{A1}$$

where

u = bulk water velocity along the axis of the heat exchanger,
v = bulk water velocity in the radial direction,
z = verticaal coordinate along the axis of the heat exchanger, and
r = radial coordinate.

Momentum, z–direction

$$\rho\, u \frac{\partial u}{\partial z} + \rho v \frac{\partial u}{\partial r} = \frac{\partial}{\partial z}\left[\mu \frac{\partial u}{\partial z}\right] + \frac{1}{r}\frac{\partial}{\partial r}\left[r\mu \frac{\partial u}{\partial r}\right] - \frac{\partial P}{\partial z} + S_z \tag{A2}$$

where

$$S_z = -\rho_{ref} g\beta(T - T_{ref}) - \left[\frac{150\mu(1-\epsilon)^2}{(\phi_s D_p)^2 \epsilon^3} + \frac{1.75\rho\ (1-\epsilon)}{\phi_s D_p \epsilon^3}|u|\right](u - u_c) \tag{A3}$$

or

S_z = a bouyancy term–a viscous resistance term–a form dray term
u_c = velocity of the coal along the z–axis
ρ = density of the water (ρ_w)
μ = viscosity of the water,
p = pressure
T = water temperature
T_{ref} = some reference temperature, in this case 295k
β = the coefficient of volume expansion taken at T_{ref} (Turner, 1973)
ρ_{ref} = a reference density taken at T_{ref}
ϕ_s = a shape coefficient (for non–spherical particles)
Dp = particle diameter, assumed as D_{50} herein, or the median particle diameter by weight, and
ϵ = coal porosity.

Momentum, r–direction

$$\rho \frac{u\partial v}{\partial z} + \rho v \frac{\partial v}{\partial r} = \frac{\partial}{\partial z}\left[\mu \frac{\partial v}{\partial z}\right] + \frac{1}{r}\frac{\partial}{\partial r}\left(r\mu \frac{\partial v}{\partial r}\right) - \frac{v}{r^2} - \frac{\partial P}{\partial r} + S_r \qquad \text{(A4)}$$

where

$$S_r = -\left[\frac{150\mu(1-\epsilon^2)}{(\phi_s D_p)^2\epsilon^3} + \frac{1.75\rho(1-\epsilon)}{\phi_s\ D_p\ \epsilon^3}\ |\ v\ |\right]v \qquad \text{(A5)}$$

Energy of the Water Phase:

$$\rho u \frac{\partial T}{\partial z} + \rho v \frac{\partial T}{\partial r} = \frac{\partial}{\partial z}\left[\frac{k}{c_p}\frac{\partial T}{\partial z}\right] + \frac{1}{r}\frac{\partial}{\partial r}\left[\frac{rk}{c_p}\right]\frac{\partial T}{\partial r}$$

$$- \frac{hA}{c_p}(T - T_c) \qquad \text{(A6)}$$

where

k = conductivity of the coal pardticles,
c_p = heat capacity of the coat at constant pressure,
h = heat transfer coefficient, and
T^c = temperature of the coal.

In addition, similar to the one–dimensional analysis, the interparticle heat transfer is modeled using a convective heat transfer coefficient h. The equation describing the energy transport from water to the coal particles is described by the following equation:

Energy Equation of the Coal Phase:

$$\rho_c\ u_c \frac{\partial T^c}{\partial z} = -\frac{hA}{c_p}(T^c - T) \qquad \text{(A7)}$$

where the subscript c indicates coal. The axial velocity of the coal phase is assumed to be constant with zero radial velocity.

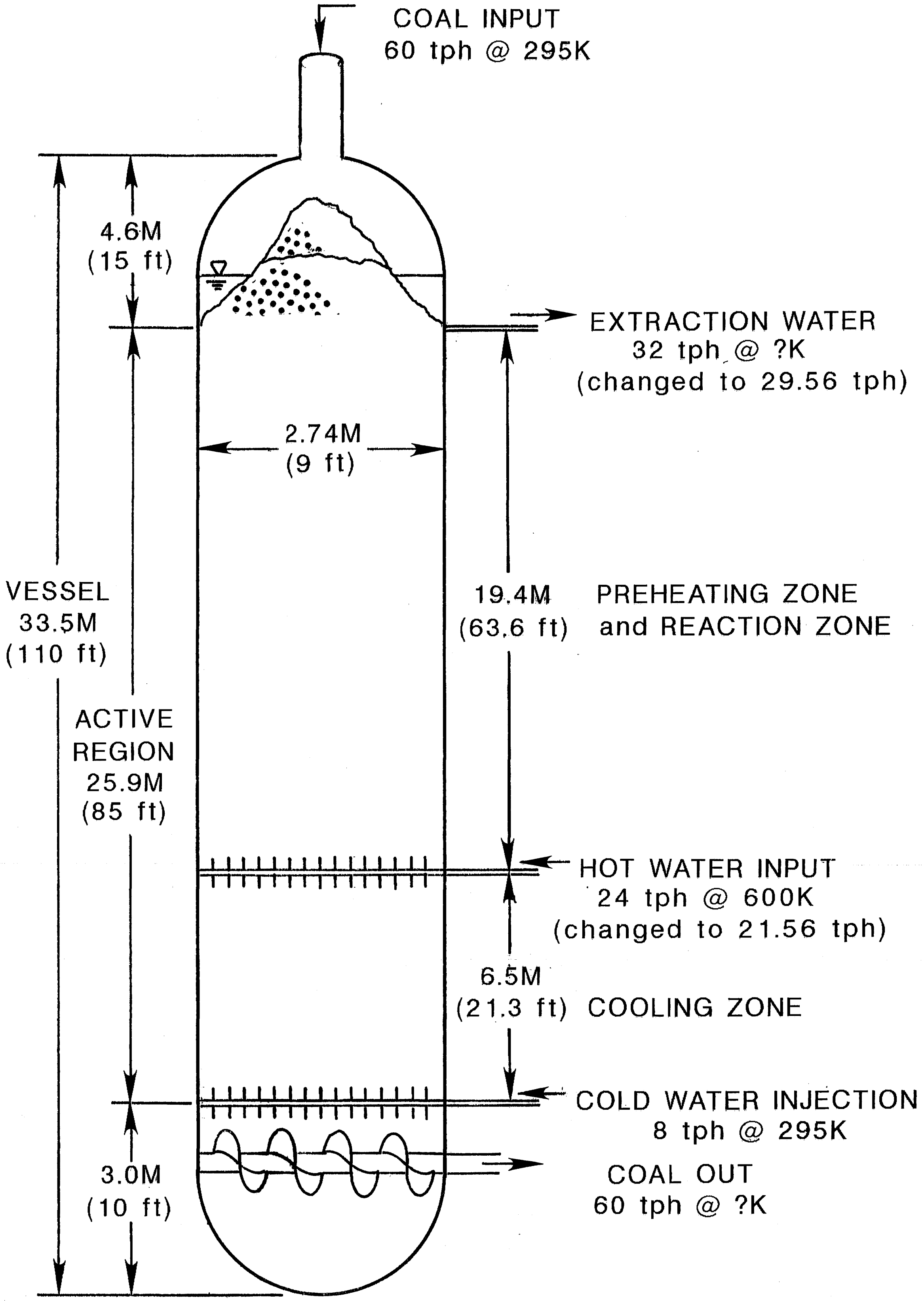

Fig. 1 ELFUEL hot-water coal reactor with the initial dimensions andmass inputs and outputs.

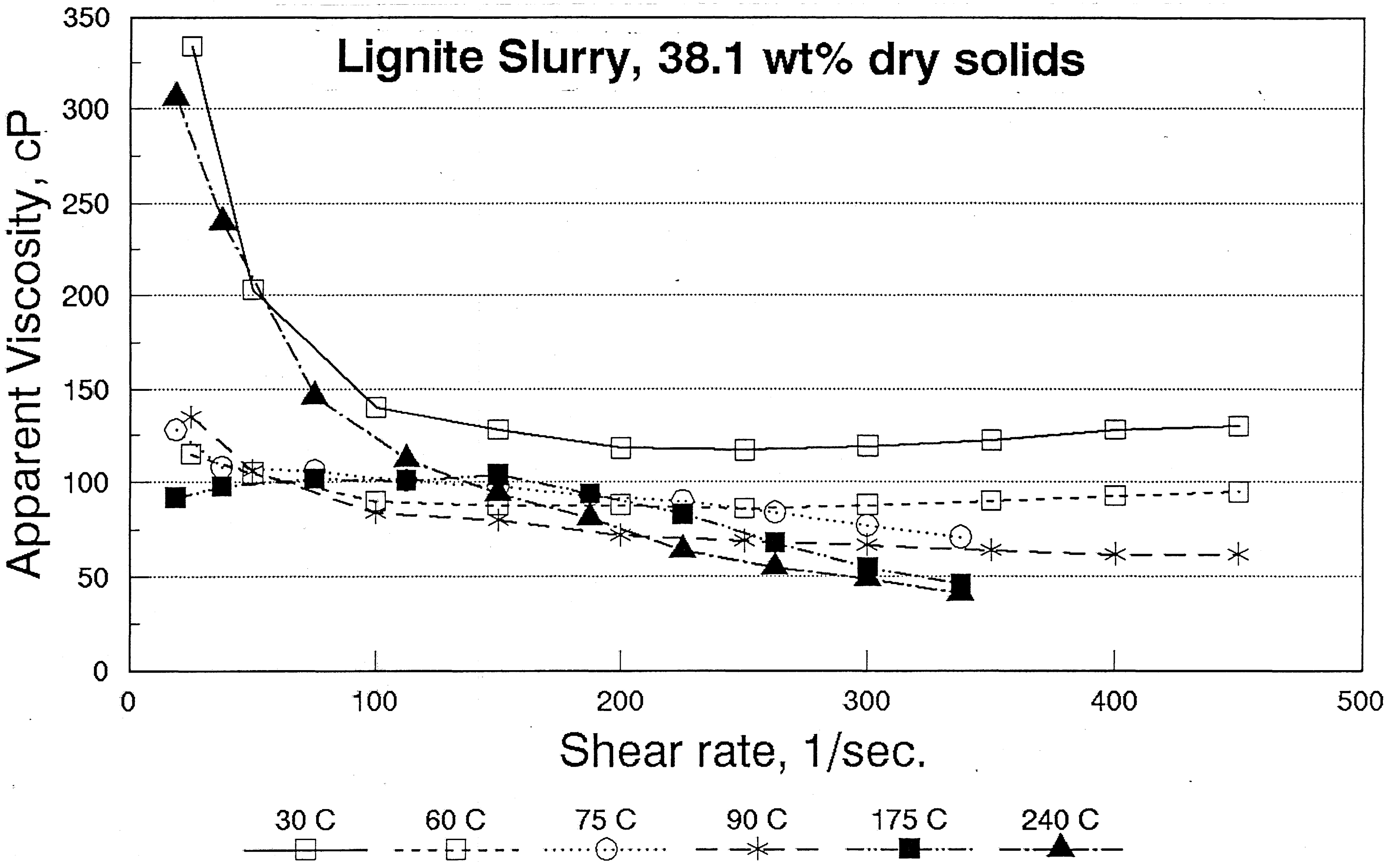

Fig. 2 Apparent viscosity vs. shear rate for raw BNI (Potas, 1990).

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UNIVERSITY OF MINNESOTA
SEDIMENT SIZE DISTRIBUTION

Tested by : KFW
Date of Test : 5/10/90 — 5/17/90
Method of Test : ASTM - COAL

Serial No.:
Source :
Remarks : Cu ≅ 7.87
Cc ≅ 1.38

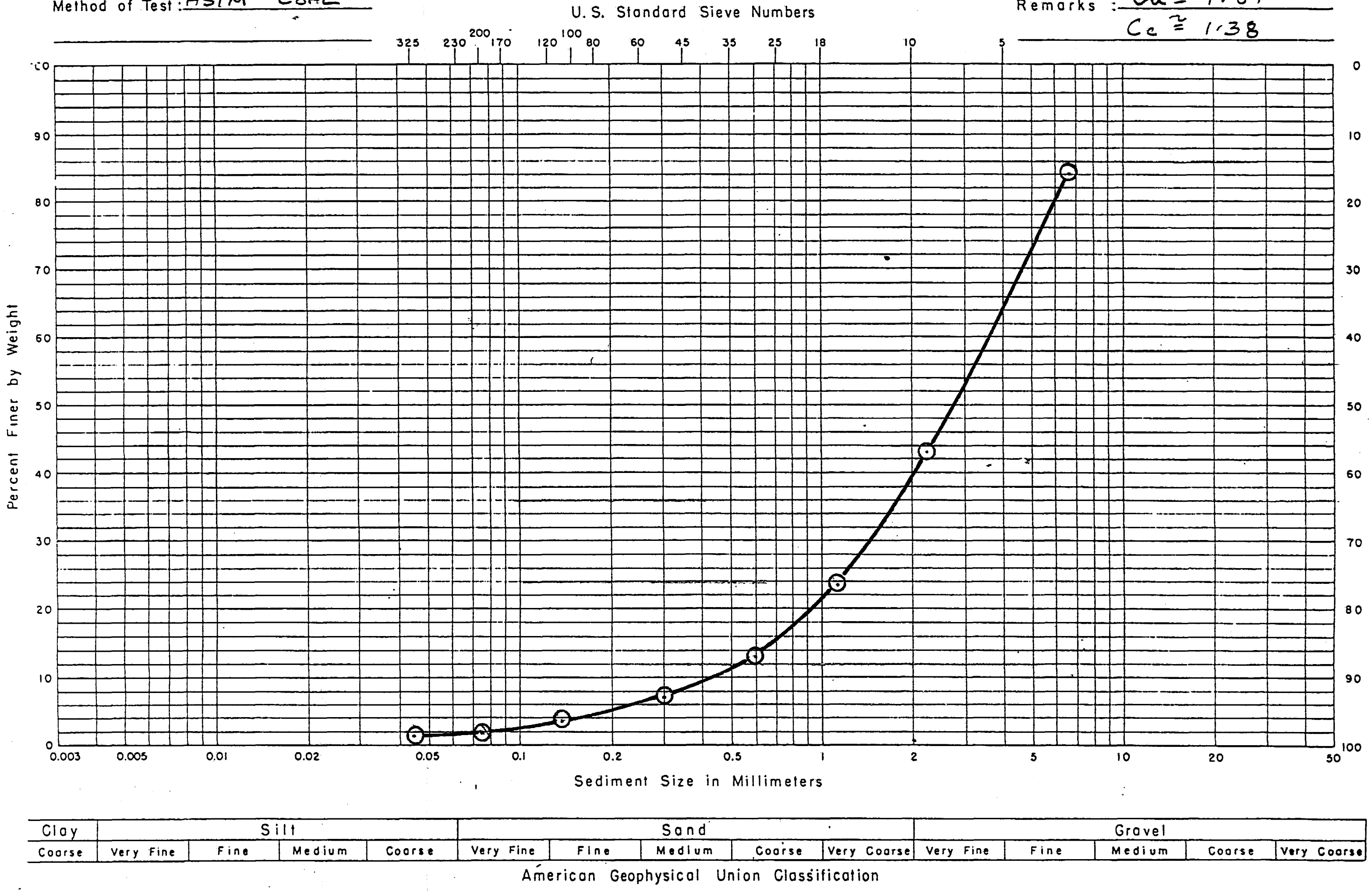

Fig. 3 Size distribution of the BNI 3XO Coal.

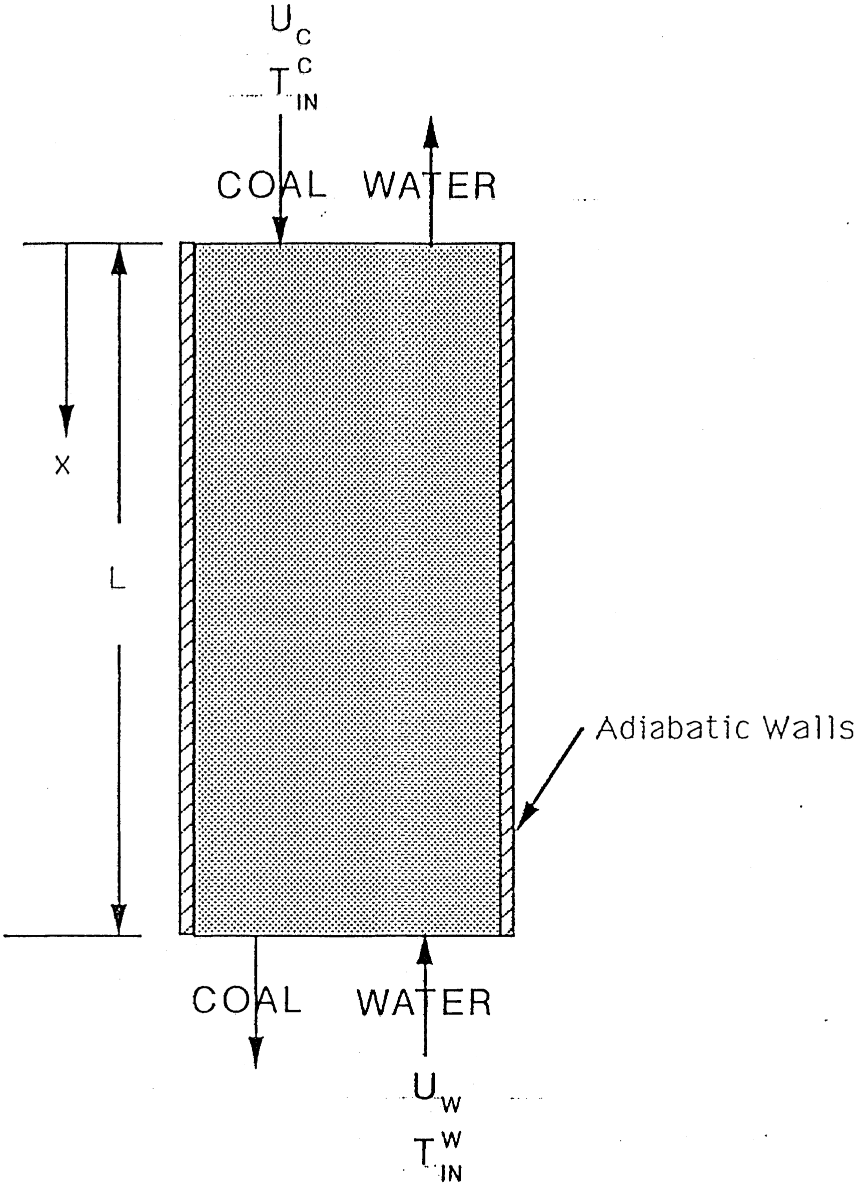

Fig. 4 Counter current solid-liquid heat exchanger.

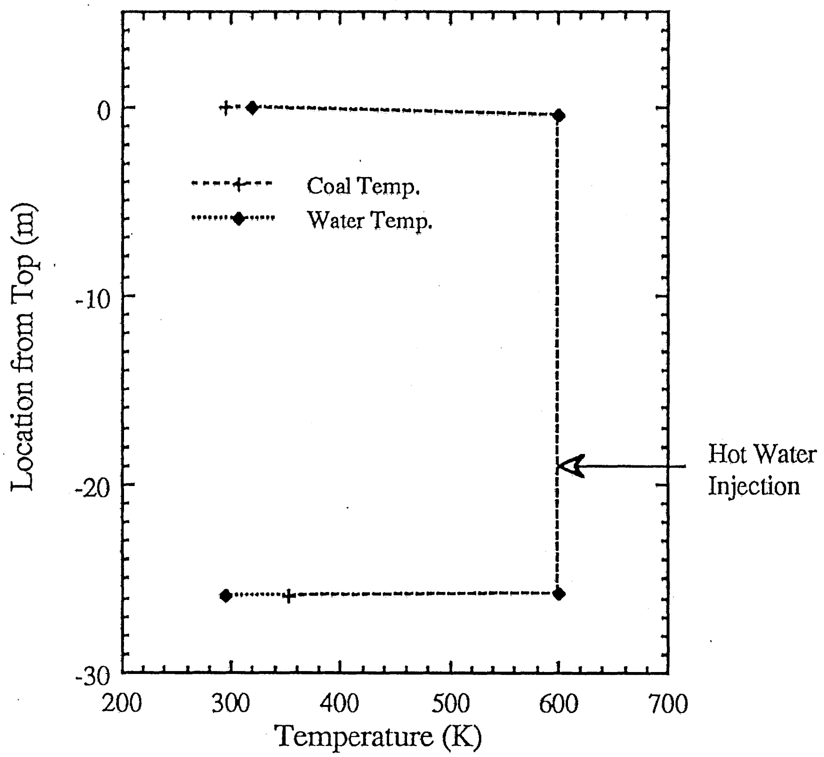

Fig. 5 Temperature profiles of the ELFUEL lignite dryer with loading 8 of 60 tph of lignite, 24 tph cooling water and 8 tph heating water.

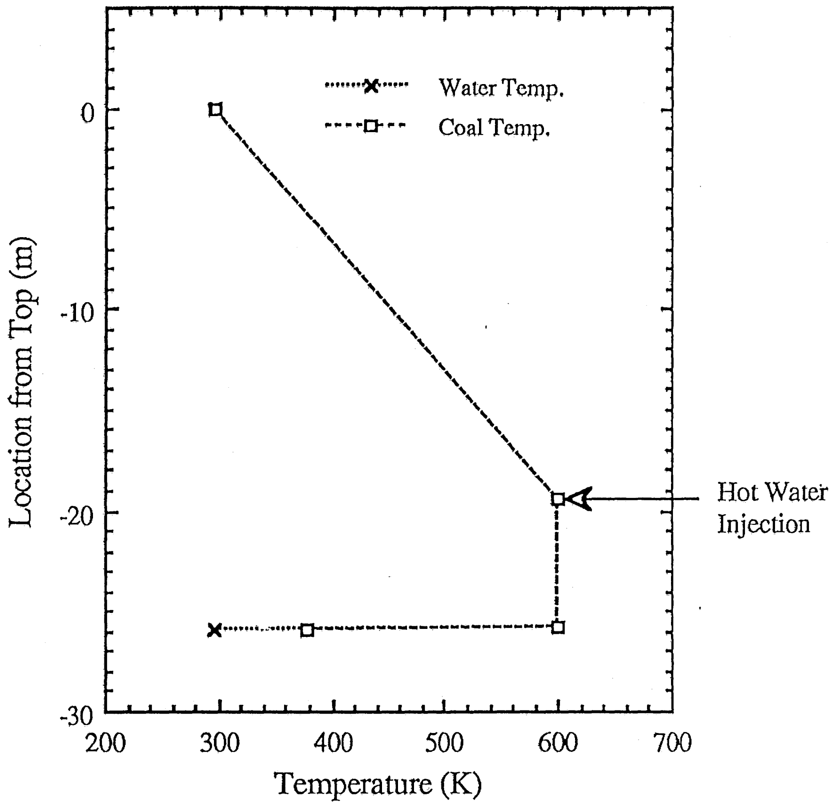

Fig. 6 Temperature profiles of the ELFUEL dryer with loading of 60 tph lignite, 8 tph hot water injection, and 21.56 tph cold water.

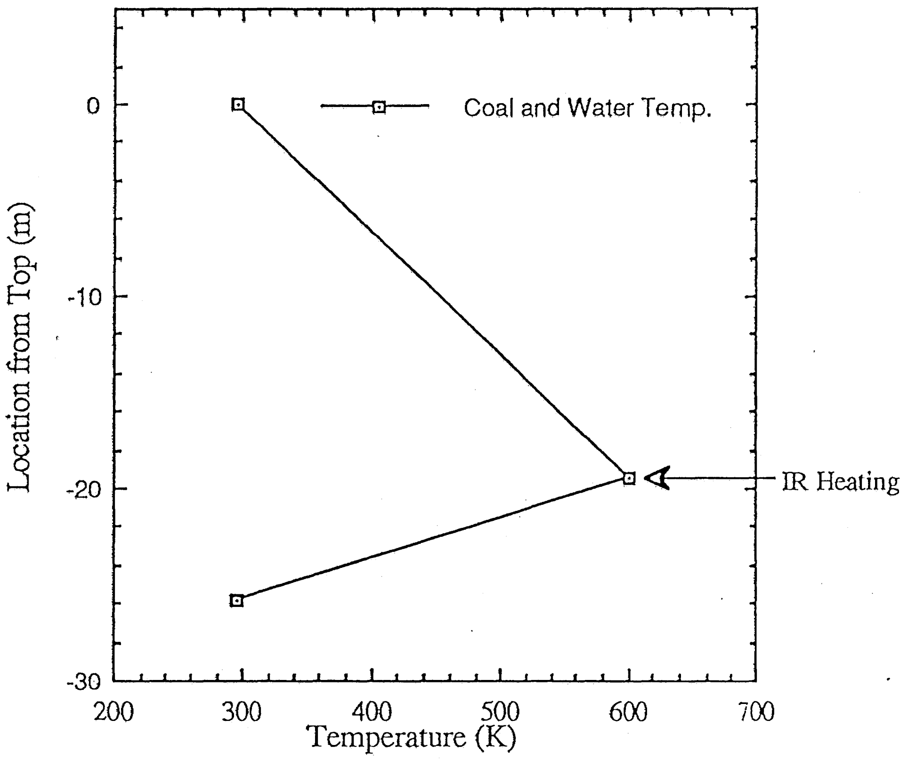

Fig. 7 Temperature profiles of the **ELFUEL** dryer 8 with IR heating and loading of 60 tph lignite, and 29.56 tph cooling water.

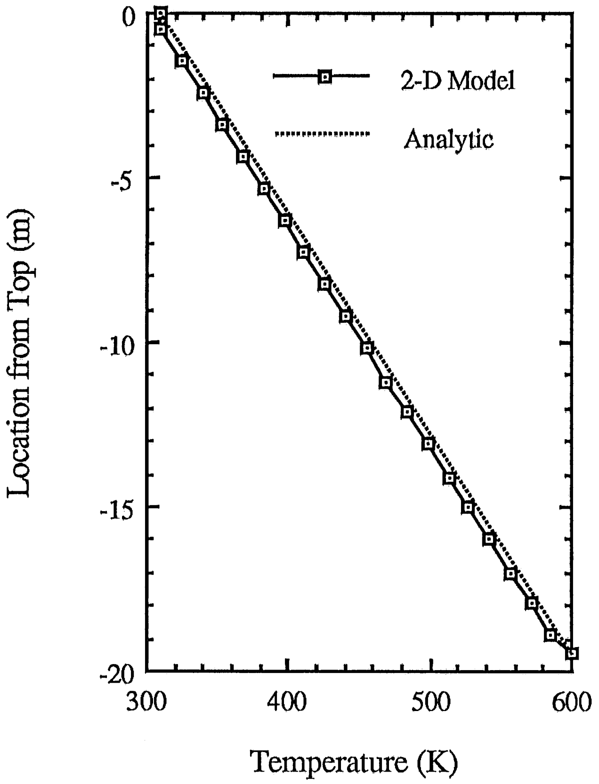

Fig. 8 Comparison of two-dimensional model and analytical model results.