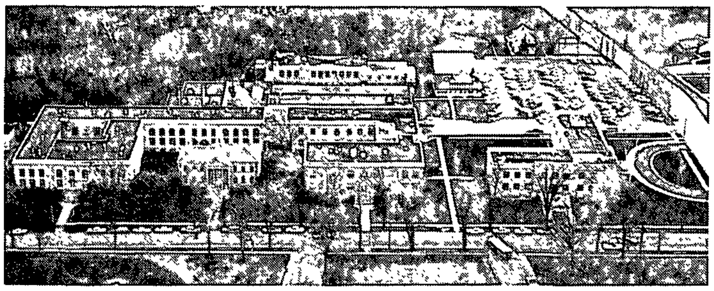

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TRAC: A COMPUTER MODEL TO ANALYZE THE TRAJECTORY AND COMBUSTION BEHAVIOR OF BLACK LIQUOR DROPLETS

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TRAC: A COMPUTER MODEL TO ANALYZE THE TRAJECTORY AND COMBUSTION BEHAVIOR OF BLACK LIQUOR DROPLETS

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ABSTRACT

At The Institute of Paper Chemistry we are developing a computer model of the lower part of a kraft recovery furnace. The model will address the gas flow patterns, temperature, and composition; the combustion of black liquor on the smelt bed; and the combustion of black liquor drops in-flight. This paper describes TRAC, which is a model to predict the trajectory and combustion behavior of black liquor droplets. TRAC models the drying, volatile burning, char combustion, and inorganic reaction stages of black liquor droplets, or particles.

The model was used to determine the effect of the initial drop diameter on the flight path and state of black liquor drops. TRAC showed that the minimum drop diameter was primarily controlled by the upward gas velocity, and the maximum drop diameter was controlled by the amount of time required to dry the black liquor drops.

INTRODUCTION

Black liquor, which is a by-product of the kraft pulping process, is combusted to get rid of the organic material, recover the inorganic pulping chemicals, and to produce steam. The liquor is burned in recovery furnaces, which are expensive to construct and are subject to explosions (1). Consequently, many mills would like to improve the capacity, safety, and efficiency of their recovery furnaces. In order to do this, a better understanding of the processes that occur in the recovery furnace is required.

An extensive effort is under way at The Institute of Paper Chemistry (IPC) to model the combustion of black liquor in a kraft recovery furnace. The furnace model is being developed in three separate parts, which will eventually be tied together. The first part is a computer model to predict the gas velocity, temperature, and chemical composition in the lower part of a recovery furnace. The second part is a model to predict black liquor burning on the char bed, which will be a boundary for the gas phase model. The third part is a model to predict the in-flight combustion of black liquor drops.

This paper describes the droplet trajectory and combustion model (TRAC), and the use of TRAC to predict the parameters that have the greatest effect on the fate of the droplets in a recovery furnace. In the future, TRAC will be interfaced with the gas phase model to predict the exchange of mass, momentum, and energy between the droplet and gas phases. TRAC predicts the trajectory of individual droplets and the associated rates of droplet drying, volatiles burning, char combustion, and the inorganic reaction phase.

Two previous models, by Merriam (2) and Shick (3), have been developed to predict the combustion behavior of black liquor droplets in a recovery furnace. These models have been useful in determining the effect of some parameters on liquor combustion. However, both models lack the fundamental data required to model the four burning stages. TRAC is an improvement over these two models due to the access to new data from ongoing experimentation at IPC and other institutions.

In the model developed by Merriam for the American Paper Institute, the droplets were assumed to swell linearly during drying. However, data from the National Bureau of Standards (NBS) shows that black liquor droplets increased in diameter by 1.5 times after about 0.2 s (4). This paper shows that the assumed droplet diameter during drying has a large influence on the drying rate and hence the eventual fate of the black liquor. In his kinetic expressions for volatiles and char burning, Merriam resorted to using parameters derived for coal. Work on char combustion by Grace et al. (5) showed that the carbon in kraft char burns at a much different rate than for carbon in coal. Merriam was also unable to develop a fundamental expression for determining droplet temperatures, which makes the Arrhenius rate expressions he used susceptible to errors.

In Shick's model (3), the droplets were assumed not to swell during drying, and as this paper shows, swelling has a significant effect on drying times. Shick assumed that the rate of devolatilization was a function of the bulk gas temperature. However, Hupa et al. (6) and Crane and Clay (7) report little effect of gas temperature on the reaction rate. Shick used an empirical expression for the rate of char burning which did not match the rates observed experimentally (5,6).

TRAC uses the data generated at NBS for the droplet diameters during drying, and predicts drying times which are shorter than those found by Merriam and Shick's models. For the volatiles burning stage, TRAC uses an empirical expression for mass loss which was developed through a laboratory study of black liquor burning. TRAC avoids the difficulty in predicting the local reaction particle temperatures, which are required in the kinetic expression for the rate of char burning, by using an oxygen mass transfer rate to determine the rate of char burning.

BASIC EQUATIONS

In TRAC, the droplets are assumed to pass sequentially through the drying, volatile burning, char combustion, and inorganic reaction stages. The initial mass of water, volatiles, fixed carbon, and inorganics in the droplet are specified by the user. A sample composition is shown in Figure 1. The mass of the droplet (or particle) determines the stage of combustion the particle is in. Specific equations are used for the changes in particle mass and diameter during each stage so that the state of the liquor is predicted as a function of time. The equation of motion is used to determine the position of the droplet, also as a function of time. By combining the equations, TRAC predicts the state of the liquor in a recovery furnace environment as a function of time.

Figure 1 here

EQUATION OF MOTION

The equation of motion for a droplet is derived from a force balance on the droplets, and is given in Eq. (1). The only forces considered are the drag and the gravity forces. In TRAC, Eq. (1) is solved numerically by integrating the equation over small discrete time steps. Once the droplet velocity has been determined, the droplet position can be easily solved. The droplet drag coefficient (C_D), mass (m), projected area (A_d), the direction of the force acting on the droplet from the gas (U_i-V_i), and the magnitude of the difference between the gas and particle velocity $|U_i-V_i|$ are also determined at each time step. The density of the gas phase (ρ_g) is set as a function of temperature.

$$m(dV_i/dt) = [C_D \rho_g A_d (U_i-V_i)|U_i-V_i|]/2 + mg \qquad (1)$$

where $i = x, y, z$.

The drag coefficient is a function of the Reynolds number (Re), as is given in Eq. (2) and (3). The changes in the droplet mass and diameter depend on the stage which the droplet is in, as given below.

$$C_D = 28/Re^{0.75} \qquad 0.5<Re<30 \qquad (2)$$

$$C_D = 12/Re^{0.5} \qquad 30<Re<700 \qquad (3)$$

DRYING

The data of Hupa _et al._ (_6_) show that drying times for 0.75 to 2 mm diameter droplets are linearly related to the droplet diameter. An analysis of the data shows an excellent correlation between the drying times and the temperature to the fourth power. This agrees with the concept that the drying rate of the droplets is limited by the heat transfer to the droplets (_1_), at least for a radiant heat flux environment. If the drying rate is externally heat transfer controlled, then the mass loss during drying can be described by Eq. (4). The convective heat (Qc) and the radiative heat flux (Q_R) are a function of the droplet state and its environment. The latent heat of vaporization of water (H_V) is assumed to be constant. Since liquor is sprayed into the furnace very close to the vaporization temperature of the water in the droplets, the sensible heat is ignored.

$$dm/dt = -(Qc + Q_R)/H_V \tag{4}$$

The convective heat flux to a particle passing through a gas stream is given by Eq. (5), where (S) is the droplet surface area, (Tg) is the gas temperature, and (Td) is the droplet temperature. The heat transfer coefficient (h) for gas flow over a sphere can be calculated by dimensional analysis, as shown in Eq. (6), where (k) is the thermal conductivity of the gas, and (D) is the droplet diameter. The Nusselt (Nu) number for flow past a sphere is given in Eq. (7).

$$Qc = h\ S\ (Tg - Td) \tag{5}$$

$$h = k\ Nu/D \tag{6}$$

$$Nu = (2.0 + 0.6\ Re^{0.5}\ Pr^{0.33}) \tag{7}$$

The radiative heat flux to the droplets in a recovery furnace is described by Eq. (8). The terms on the right hand side of Eq. (8) represent the heat fluxes from the gas to the drop, from the bed to the drop, and from the wall to the drop. The equations for these terms are given in Eq. (9), (10), and (11). The gas emissivity (ε) in TRAC is a user input, and should reflect the concentrations of water vapor, carbon dioxide, and fume in the flue gases, as well as gas temperatures, and the furnace geometry. Typically (ε) should be about 0.4. The view factor (Fbd) is a variable to describe how much of the radiant energy that leaves the bed is "seen" by the droplet, and is a function of the height of the droplet above the bed. Since the sum of the view factors must equal unity, then the sum of the view factor between the walls, bullnose, roof, etc., and the droplet is 1 minus Fbd.

$$Q_R = Qgd + Qbd + Qwd \tag{8}$$

$$Qgd = \varepsilon\ S\ \sigma\ (Tg^4 - Td^4) \tag{9}$$

$$Qbd = (1 - \varepsilon)\ S\ Fbd\ \sigma\ (Tb^4 - Td^4) \tag{10}$$

$$Qwd = (1 - \varepsilon)\ S\ (1 - Fbd)\ \sigma\ (Tw^4 - Td^4) \tag{11}$$

Changes in the droplet diameter are predicted to have a large effect on the drying rate, since the convective and radiative heat fluxes are a linear function of the droplet surface area. Data compiled with the reactor at NBS indicated that swelling occurred during the first 0.4 m traveled, or about 0.2 s (4). The diameter increase was about 1.5 times for droplets that varied from 1.4 to 2.0 mm in initial diameter. However, the increase in droplet diameter could vary between 1.1 and 1.8 times. In TRAC, the diameter of the droplets during drying is given by Eq. (12) and (13). The swelling of the droplet during drying (θ_D) is a user input, and (D_i) is the initial drop diameter.

$$D = D_i \qquad t<0.2\ s \tag{12}$$

$$D = D_i\ \theta_D \qquad t>0.2\ s \tag{13}$$

There is very limited data on the droplet surface temperatures (Td) during drying in a recovery furnace environment. However, data show that the liquor will begin to pyrolyze at about 300°C (8). Since there are no reports of extensive devolatilization during the early stages of drying, this indicates that Td remains relatively constant, at least during the initial drying stage. TRAC assumes that there is enough circulation within the drop when the droplet solids content is less than about 90% so that the drop surface temperature does not increase significantly.

Clay *et al.* (4) and Hupa *et al.* (6) report that volatile burning begins before the droplets are completely dried. Also, the droplets begin to swell rapidly at the end of the drying phase. This behavior is accounted for in TRAC by applying the drying equations for the changes in diameter and mass up to a user defined solids content, after which the droplets enter the volatile burning period.

VOLATILES BURNING

During the volatile burning period, hundreds of reactions occur (8). Among others, there is cleavage of alkyl, carbonyl, and carboxyl groups, and degradation of the aromatic rings in lignin. This leads to the evolution of volatile gases such as CO, CO_2, H_2, CH_4, and reduced sulfur compounds. Coal researchers have successfully applied pseudokinetic models to predict the rate of mass loss during coal devolatilization (9).

The kinetic approach has limited use in predicting the devolatilization of black liquor droplets due to the difficulties in predicting a characteristic reaction temperature. There are temperature gradients within the drop and the very high heat fluxes to the drop can change the droplet temperature rapidly.

Hupa et al. and Crane and Clay's (7) work show that the bulk gas temperature has only a small effect on the droplet devolatilization rate. Hupa et al. attributed this observation to the relative unimportance of the reactor bulk gas temperature compared to the temperature of the burning volatile gases surrounding the droplet. Crane and Clay reported a trend toward faster devolatilization rates at higher oxygen concentrations.

Due to the limitations of the kinetic approach, TRAC uses an empirical expression which was formulated by Crane and Clay. This equation was developed for the combustion of single black liquor drops in a convective mode. The mass loss with time (dm/dt) is given in Eq. (14). The rate is a function of the solids content of the liquor (SC), the initial mass of the droplet (mi), the initial droplet diameter (D_i), and the oxygen concentration (O_2) in the bulk gas stream. This equation was found to give good agreement with the volatile burning rates for droplets with initial diameters in the range of 2.3 to 3.7 mm. Calculations for a droplet with an initial diameter of 0.75 mm show that this equation predicts volatile burning times that are about 50% less than those found by Hupa _et al._, where the droplets were surrounded by stagnant gases. However, there was considerable variation in the volatile burning times between droplets of the same liquor (_7_) and between different liquors (_6_). At an oxygen concentration of 10% the equation breaks down for droplets greater than 5.3 mm. However, droplets of this size will probably not be dried in-flight in a recovery furnace, and would never reach the volatiles burning stage. Therefore the equation was used in TRAC keeping in mind that this equation was developed for a specific liquor and the devolatilization rates for other liquors may vary.

$$dm/dt = -[SC \times mi] \times [1.634/Di + 0.034\ O_2/D_i - 0.0054\ O_2 - 0.316] \qquad (14)$$

Black liquor droplets swell rapidly during the volatile burning stage. The composition of the liquor has been shown to effect the relative amount of swelling (_6_). However, the swelling phenomenon is not well enough understood to model the diameter increase during the volatile burning period. In TRAC, the droplet diameter is assumed to increase linearly during the volatile burning period with the droplet reaching its maximum diameter at the end of volatile burning, as shown in Eq. (15). The maximum increase in droplet diameter (θV) is a user defined parameter. The relationship between mass of the droplet at the end of the drying period (mD), the current drop mass (m), and the mass of the droplet at the end of the volatile burning period (mV) determine how far swelling has progressed.

$$D = D_i \cdot \theta_D + D_i \, [\theta V - \theta D] \, \frac{mD - m}{mD - mV} \qquad (15)$$

CHAR COMBUSTION

After devolatilization, some of the carbon remains in the drop as fixed carbon. This carbon reacts with oxygen that diffuses from the bulk furnace gases to the particle. For this type of heterogeneous reaction, the overall rate may be limited by the chemical kinetics of the reaction or by the oxygen mass transfer rate to the char particle. Grace _et al_. (_5_) reported that the burning of char particles in a single particle reactor was oxygen mass transfer limited. TRAC uses an expression for mass transfer limited burning as given in Eq. (16) to predict mass loss rates during char burning, and this equation was found to give good agreement with experimental results (_5_,_6_). The rate of mass loss is a function of the droplet surface area (S), the concentration of oxygen in the bulk flue gas (Co), and a parameter (Φ) which defines the ratio of CO to CO_2 in the product gas. The variable (ko) is the oxygen mass transfer coefficient which is arrived at through a Sherwood number (Sh) correlation as shown in Eq. (17). The diffusion coefficient (Di) is determined for O_2 in air, and is a function of temperature. The Sherwood number is calculated with Eq. (18) where (Sc) represents the Schmidt number.

$$dm/dt = -ko \; S \; Co \; \Phi \qquad (16)$$

$$ko = Sh \; Di/D \qquad (17)$$

$$Sh = 2.0 + 0.5 \, (Re^{0.5} \, Sc^{0.333}) \qquad (18)$$

As the carbon in the droplet burns out, the remaining molten salts begin to coalesce into a smelt bead. In TRAC, the droplet diameter during char combustion is described by Eq. (19).

$$D = Di \left[\theta v - \left\{ (\theta v - \theta s) \frac{mV - m}{mV - mC} \right\} \right] \qquad (19)$$

The ratio of the diameter of the smelt bead to the initial drop diameter is represented by (θs), and (mC) is the mass of the droplet at the end of the volatile burning stage. A large decrease in the droplet mass will lead to a relatively large decrease in the droplet diameter. The density of the smelt droplets is taken to be the same as liquid smelt, which was given as 1900 kg/m^3 (10).

INORGANIC REACTIONS

At the end of the char burning period, the inorganics remaining in the particle may undergo further reactions. Grace *et al.* (5) report a small increase in the mass of the droplet due to the oxidation of sulfide in the droplet to sulfate. However, the changes in droplet mass and diameter are small enough so that they have only a minimal effect on the trajectory of the droplets.

RESULTS AND DISCUSSION

The models developed by Merriam (2) and Shick (3) showed that the initial droplet diameter has a large effect on the trajectory and state of the droplet in the furnace. The size of the black liquor droplets will also effect the performance of a recovery furnace (11). If the droplets are too small, then they will be entrained in the furnace gases and will cause plugging in the upper part of the recovery furnace. If the droplets are too large, they will land on the smelt bed before they are completely dried. Wet drops will decrease the temperature of the bed, make the bed less porous, and in an extreme case could lead to a blackout (1).

TRAC was used to evaluate the effect of the initial drop diameter on the fate of the droplets and the parameters that had the greatest influence on the minimum and maximum drop diameters that could be burned in a recovery furnace.

EFFECT OF INITIAL DROPLET DIAMETER

Figure 2 illustrates the fate of droplets with initial diameters of 0.75, 2.0, and 3.5 mm, given the conditions shown in Table 1. These diameters were chosen as they represent small, medium, and large drops. In the figure, the droplets are represented by circles showing the current droplet diameter, and the circles are drawn at 0.25 s intervals.

Figure 2 and Table 1 here

The 0.75 mm droplet burns out very quickly and becomes entrained in the upflowing furnace gases. For droplets of this size, the fate of the droplets is almost completely dominated by the upward gas velocity, with the burning characteristics of the droplets having little affect on their fate.

After the 2.0 mm droplet finishes drying it begins to swell, which causes the droplet to rapidly decelerate. During the volatile burning period, when the droplet is relatively light and fluffy, it becomes entrained in the upward flowing gases. As the carbon in the droplet burns out, the inorganics coalesce to form a relatively dense smelt bead that falls onto the char bed. Once the droplet has burned out, it takes almost 2 s before it lands on the bed, which is ample time for reoxidation of the inorganics within the particle according to the data of Grace et al. (5). The fate of intermediate size drops can either be controlled by their burning behavior, or by the furnace environment.

The 3.5 mm diameter droplet just reaches the volatile burning stage as it lands on the smelt bed. The increased drying times for larger drops delays the swelling of the drops so that they do not burn out. For larger drops, their fate is controlled by the drying rate of the drop, and is not strongly influenced by the furnace environment.

Figure 2 indicates that there is a range of drop sizes that will be large enough so that they will not be entrained, but will still dry before they land on the char bed.

MINIMUM DROP SIZE

Droplets may be entrained under two conditions. First, if the initial droplet diameter is small, then the resulting smelt bead will also be small enough so that it is entrained. The second condition is if the droplet burns out very slowly, then it may become entrained before it burns down to a smelt bead. For example, when there is a low oxygen concentration in the gases surrounding the droplet, the char burning rate will be relatively slow. Tran (12) found only small amounts of organic carbon in the carryover deposits which indicate the first condition is the most probable cause of entrainment.

Figure 3 shows the minimum initial diameter of drops that would not be entrained as a function of the upward gas velocity. In a typical recovery furnace, the bulk upward gas velocities would be about 4 m/s; however, a central core may develop with upward velocities at least twice as great (13). TRAC indicates that the minimum drop diameter is related to the gas velocity raised to a power of about 1.2. Therefore, doubling the gas velocity leads to slightly more than a doubling of the minimum drop size that would not be entrained.

Figure 3 here

Equation 16 shows that the rate of mass loss during char combustion is predicted to be linearly related to the oxygen concentration in the bulk furnace gas. In Figure 2, the oxygen concentration was set at 10%, which allows the droplets to burn out quickly. However, in cases where the secondary air jets do not penetrate into the center of the furnace, an oxygen deficient core may develop (13). Droplets that become entrained in this oxygen deficient central core would burn out slowly and TRAC predicts that they may become entrained. A similar phenomenon would occur for liquors which have slower volatile burning rates, since the droplets would remain in the fluffy state for a longer period of time.

The amount that the droplets swell during the volatile burning period does not necessarily affect the minimum drop size that will be entrained. The minimum drop size is primarily determined by the upward gas velocity and is not greatly affected by the combustion behavior of the drops. Part of the reason for this is that droplets that swell more will burn out faster, since they have a greater surface area (6).

MAXIMUM DROP SIZE

If the droplets are too large, they will not dry before they land on the smelt bed. For the conditions used in generating Figure 2, the maximum drop size that could be dried is 3.8 mm. However, in a recovery furnace, the maximum diameter would depend on the initial droplet velocity, the solids content of the liquor, the furnace temperature, and the amount that the droplet swells during drying.

When large drops, which will not dry in-flight are burned in a recovery furnace, the spray nozzle pressure is increased, which gives greater initial droplet velocities. Increasing the initial droplet velocity or aiming the black liquor guns slightly upward will cause the droplets to impact on the furnace wall, where they will dry before falling to the smelt bed. This is illustrated in Figure 4, for a 3.5 mm drop. In case A, the droplet has a horizontal velocity of 10 m/s; in case B, the horizontal velocity was 12 m/s; and, in case C, the horizontal velocity was also 10 m/s, but the vertical velocity was 2 m/s. In cases B and C, the droplet hits the wall before it is dry. However, the figure shows that in these cases, these droplets also spend less time in-flight so that less use is made of drying in the furnace cavity, where drying rates would be greater than when the liquor is stuck on the wall.

Figure 4 here

The drying time for a droplet of a given diameter will decrease if the droplets are fired into the recovery furnace at a higher solids content. Consequently, the maximum drop size could be increased, as the droplets would reach the volatile burning period sooner. The drying rate is also determined by the ambient temperature as is shown in Eq. (4). When the temperature in the furnace cavity is increased, then larger drops can be dried in-flight. Table 2 shows the maximum initial diameter for a droplet that would just dry in-flight, as a function of the solids contents of the liquor and the furnace gas temperature. The table shows that even relatively large drops could be dried in-flight at higher solids contents. This would contribute to the increased performance of furnaces operating with higher solids liquor (<u>14</u>). The table shows that increasing the gas temperatures leads to only relatively small decreases in drying times.

Table 2 here

As discussed previously, the droplets swell during the drying stage. However, the measured amount of swelling varied from a 1.1 to a 1.8 increase in diameter. In Figure 2, the diameter increase during drying was set at 1.5 times, and a 3.8 mm droplet would just dry before landing on the smelt bed. Figure 5 shows the maximum drop diameter that could be dried in-flight if the increase in droplet diameter was varied between 1.1 and 1.8 times with the rest of the conditions constant. There was an approximately linear relationship between the increase in diameter and the swelling factor. TRAC predicts that the swelling during drying will be an important parameter in determining the fate of the droplets in a recovery furnace. Therefore, this parameter should be determined experimentally for the liquor and conditions that are being modeled.

Figure 5 here

The swelling during drying and the liquor solids content are two of the characteristics of the liquor that affect drying times. Furnace parameters, such as the temperature and gas velocity, have a much smaller influence on drying times. The drying time is the parameter that has the greatest effect on the maximum drop diameter that could be successfully burned in a recovery furnace.

CONCLUSIONS

TRAC is in agreement with previous models that predict the large effect of initial drop diameters on the trajectory and state of the droplets within a recovery furnace. TRAC predicts that small droplets will be entrained, and the upward gas velocity is the parameter that has the largest effect on droplet entrainment. Droplets may also become entrained if they burn out very slowly. The maximum drop diameter that can be dried in-flight is primarily a function of the drying time for the drop. Drying times are strongly influenced by the solids content of the liquor and the swelling of the liquor during drying. The temperature in the furnace has a smaller influence on the drying times.

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FIGURE CAPTIONS

Figure 1. Typical composition of a black liquor droplet showing the components that are modeled in TRAC.

Figure 2. Trajectory and state of a small, intermediate, and large droplet in a simulated recovery furnace environment.

Figure 3. The minimum initial diameter for a drop that will not be entrained as a function of the upward gas velocity.

Figure 4. Effect of the initial droplet velocity on the trajectory of a 3.5 mm diameter drop.
Case A: V_x = 10 m/s, V_y = 0 m/s;
Case B: V_x = 12 m/s, V_y = 0 m/s;
Case C: V_x = 10 m/s. V_y = 2 m/s.

Figure 5. The maximum initial diameter for a drop that will just be dried as a function of the swelling of the drop during drying.

Table 1. Conditions for calculating the droplet trajectories and states shown in Figure 2.

Furnace Conditions

Upward gas velocity = 4 m/s
Gas temperature = 1000°C
Oxygen concentration = 10%
$\varepsilon = 0.4$

Furnace Dimensions

10 m wide
10 m wide

Liquor Properties

Water = 35%
Volatiles = 20%
Fixed carbon = 13%
Inorganics = 32%
Drying $\longrightarrow$ volatile burning transition = 90% solids
$\Phi = 2$ (all CO as carbon gasification product)

Characteristic Diameters

$\theta_D = 1.5$
$\theta_V = 2.5$
$\theta_s = 0.7$

Table 2. The maximum drop diameter (mm) that can be dried as a function of the liquor solids content and the furnace gas temperature.

		Solids		
		60%	70%	80%
TEMP	900°C	3.2	4.0	5.9
	1000°C	3.6	4.3	6.4
	1100°C	3.8	4.7	7.4

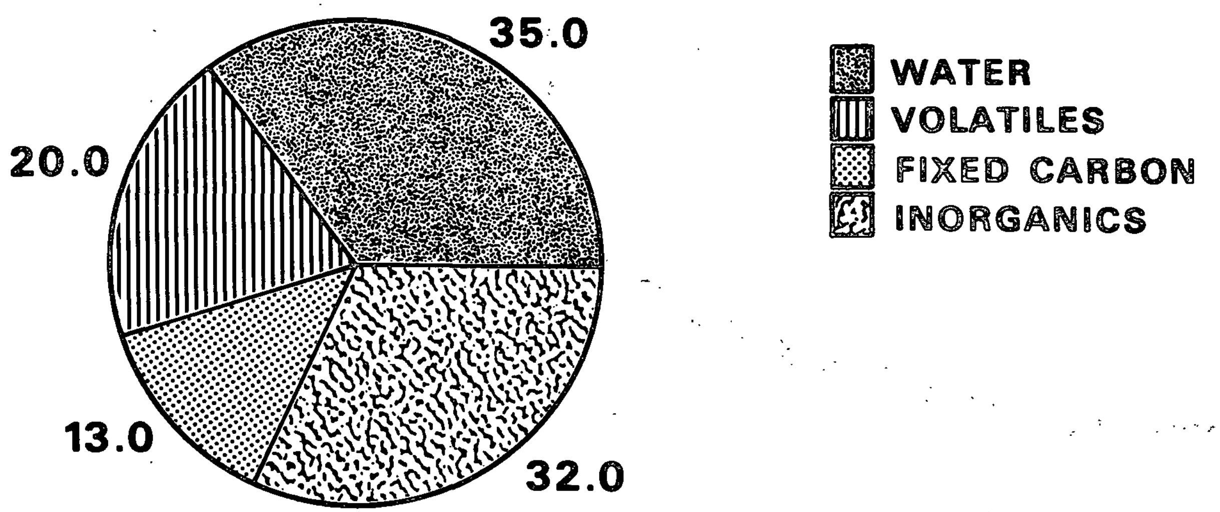

Figure 1. Typical composition of a black liquor droplet showing the components that are modeled in TRAC.

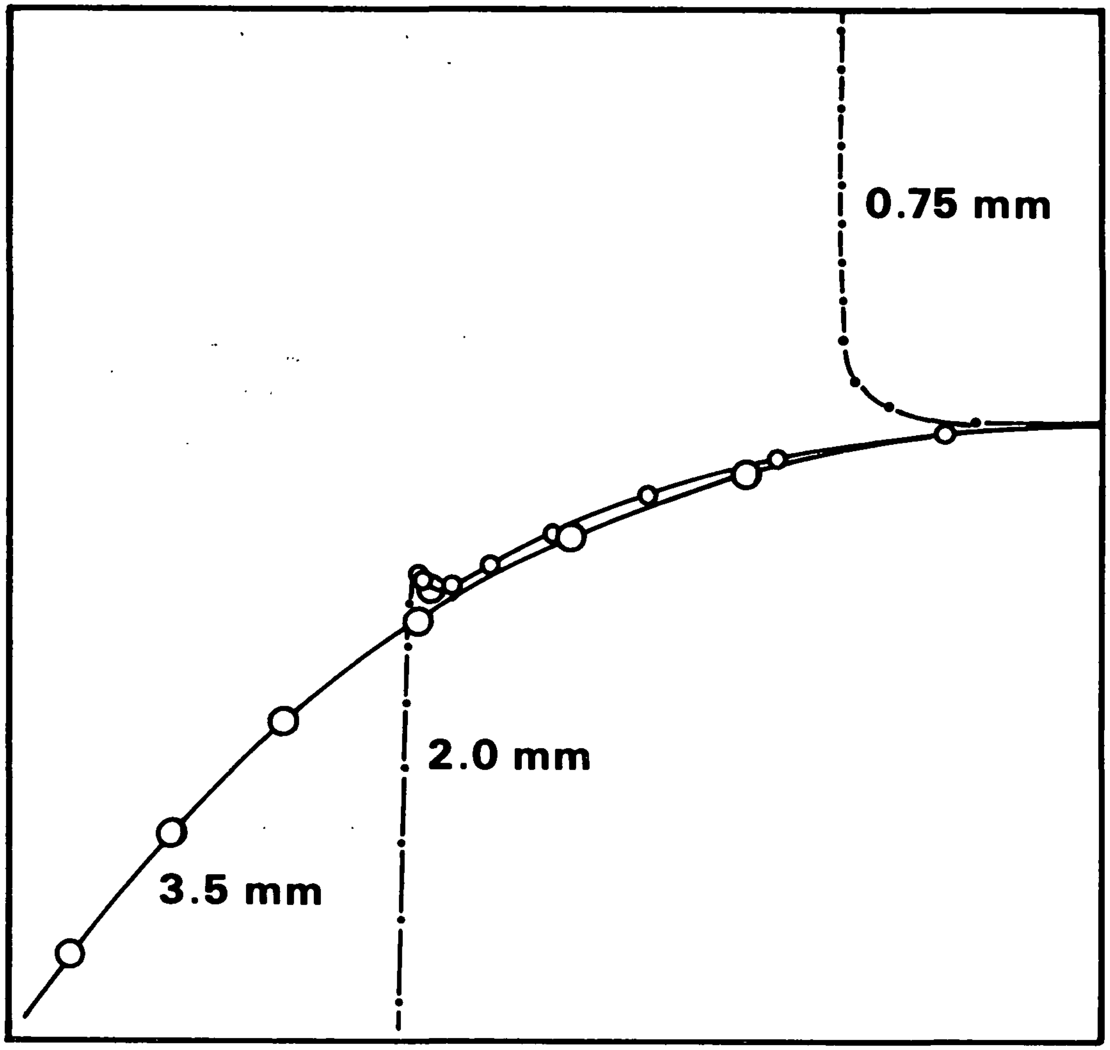

Figure 2. Trajectory and state of a small, intermediate, and large droplet in a simulated recovery furnace environment.

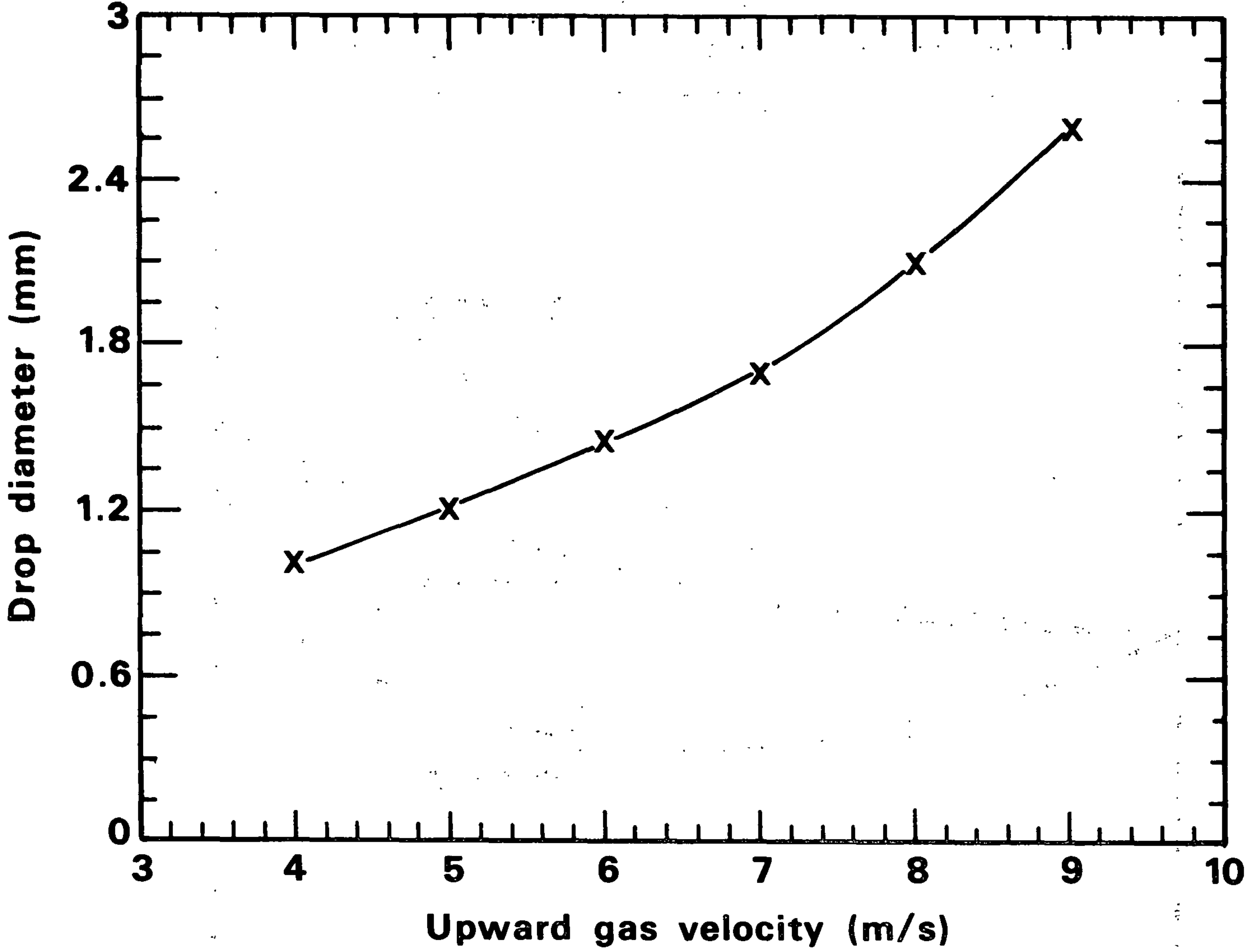

Figure 3. The minimum initial diameter for a drop that will not be entrained as a function of the upward gas velocity.

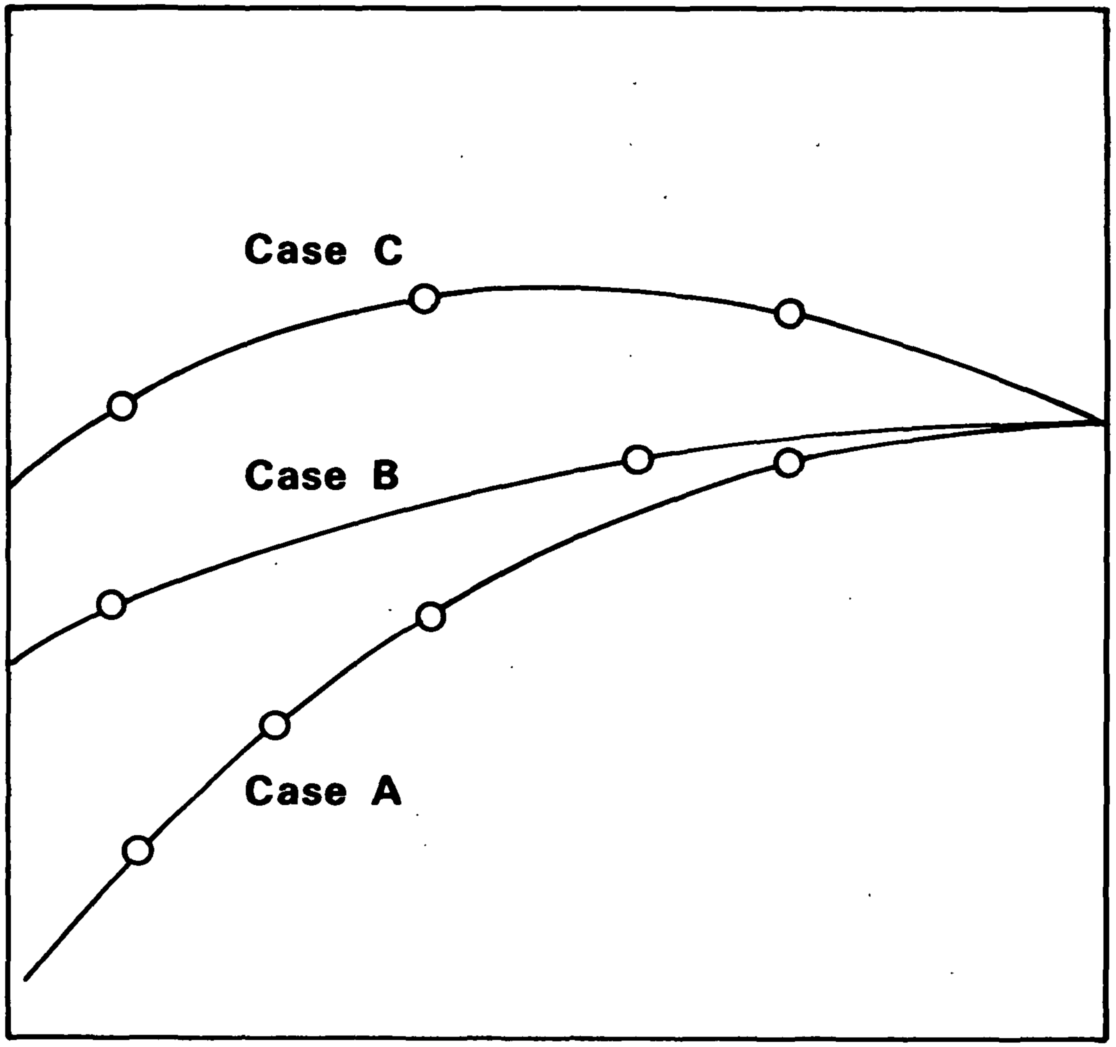

Figure 4. Effect of the initial droplet velocity on the trajectory of a 3.5 mm diameter drop.
Case A: $V_x = 10$ m/s, $V_y = 0$ m/s;
Case B: $V_x = 12$ m/s, $V_y = 0$ m/s;
Case C: $V_x = 10$ m/s. $V_y = 2$ m/s.

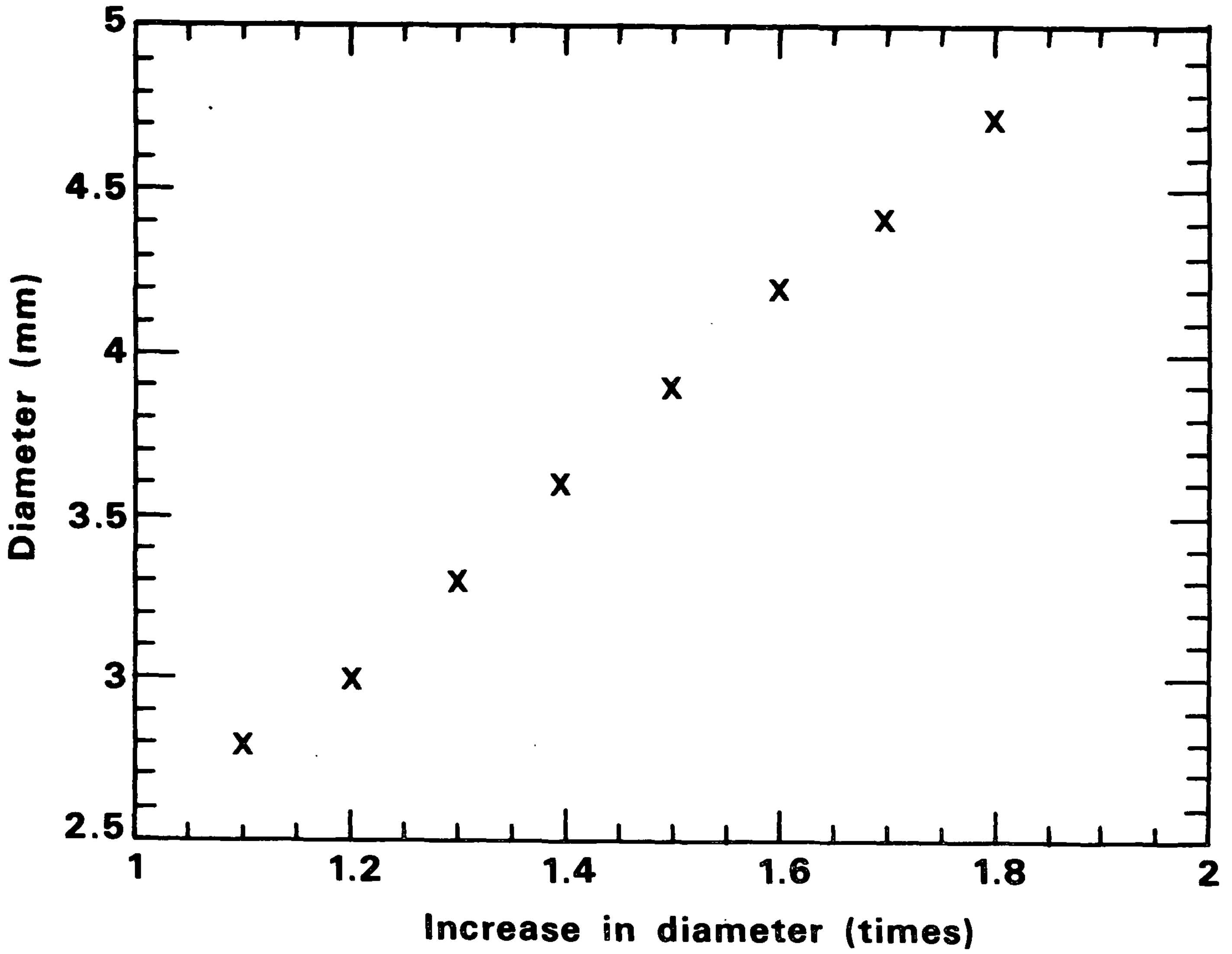

Figure 5. The maximum initial diameter for a drop that will just be dried as a function of the swelling of the drop during drying.