DISTRIBUTION MODELLING OF STOCK PREPARATION SYSTEMS FOR RECYCLED FIBERS

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ABSTRACT

Stock preparation systems for recycled papers need to be designed to produce a high quality, uniform product from a source that has significantly varying properties. Process models are a useful tool for analyzing and optimizing stock preparation systems. However, many models only account for the bulk flows of the components in the form of the fraction of fibers, contaminants, and ash. This report extends some of these modelling ideas to include component distributions. For example, the fiber fraction can be treated as a distribution based on fiber length and possibly fiber coarseness and composition. The contaminant concentration is expressed as a function of both particle size and density of the contaminant. Finally, the separation efficiency of the processing steps also becomes a function of fiber and contaminant distributions. Ultimately, these models are used to determine the efficiency of various stock preparation systems with differing configurations of the cleaners, screens, washing, and other operations. Such models allow the performance of existing and new systems to be compared and optimized, especially in the light of the changing composition of the feedstock.

INTRODUCTION

Process modelling is not a new concept. Chemical processes have been analyzed and modelled since the early days of chemical engineering. However, the development of the computer and enhancements in both speed and capacity have significantly changed the complexity and type of process models. Early process modelling, developed when computations were done by hand or with a hand-held calculator, involved relatively simple, steady-state models that incorporated a large number of simplifying assumptions to make the problem tractable. Process simulation, which is process modelling performed using a computer, uses a digital computer program to perform the necessary mass and energy balances to solve the model. The use of process simulation for process modelling has greatly extended the size of the models that can be created and solved. Process models that relied on hand calculations were generally limited to include just a handful of unit operations. Computer simulation extends the size of the models to include hundreds if not thousands of operations. Likewise, the unit operations that make up the model can be more complex and can include dynamic (time-varying) components rather than simply steady-state characteristics.

Process models and process simulations have several useful functions in the design and operation of manufacturing facilities. Modelling and simulation can aid in the design of new facilities. Models can be used to decide what size of equipment to use and to optimize the configuration and operating conditions of various unit operations. For an existing operation, models can be used to (a) optimize operating conditions for a particular unit or for an entire flow system, (b) determine the cause of process upsets and guide the engineer to the best remedial action, (c) evaluate the effect of changing process inputs (variations in the raw material), and (d) monitor an operation (1,2).

Simulations and models can be developed in a number of different ways. The development of a simulator requires the selection of software and computer platform, method for coding the data, and choice of unit operations. The most primitive type of software used is typically some type of programming language such as Pascal or Fortran. More advanced numerical software can also be used.

The development of the model can include the development of the simulator if a "prepackaged" simulator is not being used. In this case, specialized models are created that are designed for one purpose. Alternatively, simulation software can be used to develop the process model, which allows the model to be developed at a faster pace. Several simulation packages that have been developed for the pulp and paper industry are described later in this report. However, more specific simulation software constrains the user to the unit operations and flow components defined by the developer, which decreases the flexibility of the model. Developing the model from more basic software allows a greater degree of flexibility in the number and type of flow components that can be modelled, but it generally takes more effort. The more basic software also allows the user to specifically define the unit operations that are needed and easily expands to new operations.

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Modelling Tasks

One way of breaking down the functions of a model is shown in Figure 1. The following discussion assumes that a dynamic model is being considered. This is the more general case since steady-state operations can be thought of as simply a special case of dynamic operations. The primary task of this scheme is the model of the unit operation itself that contains some "states" that define its current status. The task of the unit operation model is to calculate the outputs and new states of the model, given the inputs that flow into the operation. The model may depend on parameters that are fixed (by the user) or changing (according to the changing conditions of the process).

The second task in this scheme is the determination of parameters. The parameters can be a function of the inputs to the unit operation, the current states of the unit operation, and some specified operating conditions (user input). This task may involve the translation of the user-selected conditions into the parameters necessary for the model.

The third possible task is the correlation of properties. For modelling or computational purposes, the components of the input and output streams to the operation may be expressed differently than what is important to the user. In this case, the measurements of the components of the streams need to be correlated with the properties of interest. This is the function of the box labeled "correlations."

As an example of how these three tasks work, consider a centrifugal cleaner, which is found in all pulping operations. The unit operation itself consists of the cleaner taking an input stream of pulp (which consists of pulp and contaminants) and splitting it into two output streams. The split can be thought of as depending on two parameters (reject efficiencies) that indicate the relative amount of each component that enters the reject stream. These parameters are functions of the composition of the input stream and the operating conditions of the cleaner (pressure drop, orifice sizes). Finally, the brightness of the pulp is the property of interest to the user of the model. Thus, a correlation can be used to predict the brightness of the pulp given the relative amounts of pulp and contaminants in the stream.

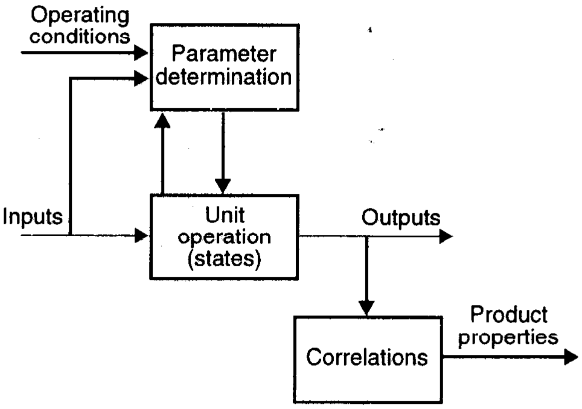

Fig. 1. Overview of process modelling paradigm.

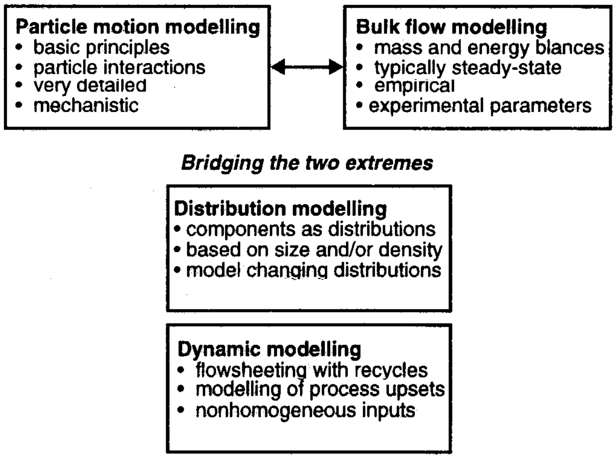

Fig. 2. Levels of detail in process modelling.

Levels of Detail for Modelling

In addition to the different tasks involved in modelling, different levels of detail can be used in creating the process model. Figure 2 illustrates two extremes in the levels of resolution. At one extreme is particle motion modelling, which describes the interactions and motions of individual particles and fibers. In this modelling, the basic principles of particle interaction are used to determine the motion of the particles. This type of modelling can be used to determine the mechanism of the equipment as well as its physical design. Interactions between particles (for example, fiber and ink particles) can also be modelled at a very high level of detail (3,4). At the other extreme is the more common type of process modelling. In this case, the models are typically steady-state and deal only with the bulk flows of the various stream components. Although this type of modelling cannot be used for the specific design of equipment, it is useful for plant designs on a larger scale. That is, the steady-state flows can be useful for determining the capacity of the equipment needed for each operation as well as the size of the piping needed between operations (1).

These extremes are bridged by a wide range of modelling possibilities that capitalize on the strengths of each model for a particular purpose. One manner of bridging the difference is to consider the component flows as distributions based on some physical property of the component. For example, fibers can be easily classified by fiber length; thus the change in distribution can be modelled through the various operations. In addition, contaminant particles vary in both density and size and can be distributed two-dimensionally along these parameters. By characterizing the components in this fashion, a greater level of detail can be obtained in the modelling without resorting to modelling the interactions of individual particles (5,6).

The two paradigms can be further combined by using the dynamic nature of the detailed particle model while modelling the component distributions. The extension to a dynamic model has several advantages. The use of steady-state models assumes consistent or at least slowly varying process inputs. The use of dynamics would allow the investigation of process disturbances, especially in processes with many recycle streams. For example, the effect of a "dirty" batch of wastepaper on the whitewater system can be investigated. Various system configurations can be investigated to design a system that is robust to highly variable inputs.

Previous Work

Modelling and simulation have been used a great deal in past work both in pulp and paper operations in general and recycling operations in particular. The following section reviews some of this work as it pertains to recycling. Some papers deal only with a specific operation and others with complete flowsheets. The papers also differ in the level of detail with which the components are modelled.

Julien Saint Amand and Perrin modelled the flotation process kinetically as a first-order process (7). In this model, they experimentally determined a flotation rate constant based on the type of contaminants, chemicals, temperature, type of pulp, temperature, bubble size distribution, and flotation cell design. These researchers also modelled a centrifugal cleaner as a first-order process based on the particle diameter at 50% efficiency (8). In this case, the model parameter depended on the cleaner dimensions, feed flow, fluid viscosity, particle density, and reject flow rate. Bliss empirically modelled the performance of centrifugal cleaners, especially with respect to fiber fractionation (9). The model in this case predicts the freeness and strength properties of the accepts and rejects streams. Wise and others determined the efficiency of cleaners based on the density and particle size of the contaminants being removed (10,11). Ferguson modelled the flow in a centrifugal cleaner on a more mechanistic level (12).

Models of washers and washer systems have also been developed. While some of these were developed specifically for brownstock washing, they are also applicable to washing and deinking. Turner and others developed a dynamic model of brownstock washer that can be combined into a countercurrent washer system (13). Doshi and Prein modelled cascades of screens and cleaners in three and more stages in order to recover fibers from the rejects streams (5). Also modelled in this work is the changing distribution of the contaminant particle size resulting from the mechanical actions of pumps and equipment. Drolet and Grenier also worked with the modelling of cascades of screens and cleaners, characterizing their performance (14).

Several researchers have worked on modelling the entire recycling process (flowsheet modelling). In general, the level of detail in this modelling has been lower; that is, flowsheet modeling has dealt mainly with bulk flows of the stream components. Moreland presented several examples of this type of modelling, including a deinking mill and boxboard clippings plant (6). Frazier and McNabb used a spreadsheet to model a deinking mill (15). This produced an easy-to-use simulation based on user-friendly software.

Finally, work has been done on the problem of predicting paper properties from pulp properties as well as characterizing the pulps in a standardized manner. Early work on characterizing mechanical pulps was defined in terms of a fiber length distribution parameter and a particle shape parameter (16). The performance attribute system of the MAPPS software deals with the task of predicting paper properties given pulp characterization (17,18). Factor analysis has also been used to correlate paper properties with measured pulp characteristics for mechanical pulps (19).

Current Simulation Systems

Many process simulators have been developed. Although most process simulators are steady-state, some do contain dynamic elements. The history of process simulation is presented in brief in an *Introduction to Process Simulation* (1). Here we describe several of the more widely used simulators. Most of these simulators can be run on personal computers; higher performance is possible on larger computer systems.

The most common simulator specific to the pulp and paper industry is MAPPS (1,20). MAPPS includes many of the unit operations used in the paper industry, including kraft digesters and recovery, stock preparation, and paper machine operations. Additionally, MAPPS contains a set of correlations that allow the prediction of paper properties from the composition of the pulp stream (17). MAPPS also includes data on wood species as well as many pulp and paper chemicals. It is capable of running whole mill simulations.

GEMS also has many of the basic models necessary for modelling pulp and paper operations (1,21), although the list is not as extensive as that for MAPPS. Like MAPPS, GEMS is capable of running whole mill simulations as well as containing data for steam, moist air, and other chemical components. Other simulators that can be used for pulp and paper mill simulations include ASPEN PLUS (22), MASSBAL (23), and FlowCalc (24). For the most part, these are steady-state simulators.

CURRENT MODELLING

Our work extends the modelling of bulk flows to include distributions of the various components based on properties important to that component. For example, the fiber component is distributed based on fiber length, so that the shortest length component represents fines while the longest represents shives. Likewise, the contaminants are characterized on the basis of density and particle size. Thus, efficiency of the separation process is also dependent on this distribution. The following sections describe the mathematical software, definition of streams, and definition of unit operations used in our preliminary modelling work.

Mathematical Software

In the current modelling work, we used MATLAB, a software package available from The MathWorks, Inc., which is designed for high performance numeric computation and visualization. MATLAB incorporates a graphical interface together with matrix computation and numerical analysis functions. The interface allows models to be created and modified without the use of traditional programming languages: models are expressed in a mathematical and matrix-oriented form. The companion software, SIMULINK, is a program for simulating dynamic systems and operates as an extension to MATLAB. Through its graphical interface, blocks (unit operations) can be defined and interconnected into any desired configuration. After a model flowsheet is created, the simulation can be run using any number of numeric integrators and the results analyzed using the full functionality of MATLAB. We are currently using MATLAB version 4.0 together with SIMULINK version 1.2c (25,26). The software is currently running on a 80486 personal computer (PC) at 66 MHz under the Microsoft Windows 3.1 and MS-DOS 6.20 operating systems.

Stream Definitions

In any modelling endeavor, the structure of the stream variables that connect the various unit operations must be defined. In our work, the composition of each stream is represented by a vector representing the total mass flow and the mass flow of each subdivision of each component. The total length of the vector is determined by the number of components being modelled and the number of divisions used for distributing the components. The first element in a stream vector is the total flow rate, which includes all the solid components and the water. The remaining elements of the vector specify the flow rates of the divisions of the various components. Thus, a model that deals with four components, each distributed into five divisions, has a vector that is 21 elements in length for the specification of the flows.

In our work, four stream components were each divided into five size divisions. The fiber component was divided on the basis of length and the contaminants on the basis of particle density (Table I). In future work, these relative sizes will be related to actual sizes through correlation with pilot-scale studies. Later in this report we present an example of a process model that involves a 120-tons/day recycling plant. Table II shows the flow rates of various pulped components from the stock tank to the screening and cleaning system. As indicated in the table, most of the very large contaminants had already been removed through the action of the perforated plates of the pulper and the junker tower. Note that the total flow rate includes the flow rates of all the components. The flow rate of water can be calculated by difference.

Unit Operations

Four unit operations are modelled in the current system: mixing, dilution, separation, and a continuously stirred tank reactor, which acts as a holding tank. Model parameters are used to vary the action of the operations. Mixing is the simplest of the operations described here. The purpose of a mixing block is to combine two streams into a single stream. Computationally, this is done by simply adding the respective flow rates for each component. (Note: Figure 6 shows an example of a mixing operation in which the incoming stock is mixed with the accepts from the secondary cleaners before being diluted and sent to the primary cleaners.)

Table I. Division of Stream Components

		Contaminant		
Division	Fiber	Heavy	Neutral	Light
1	Fillers	Very small	Very small	Very small
2	Short	Small	Small	Small
3	Medium	Medium	Medium	Medium
4	Long	Large	Large	Large
5	Shives	Very large	Very large	Very large

Table II: Flow Rates of Components From Stock Tank[a]

	Flow rate (kg/h)			
		Contaminants		
Division	Fiber	Heavy	Neutral	Light
1	200.0	19.8	19.8	19.8
2	678.9	39.0	39.0	39.0
3	1,196.2	36.0	36.0	36.0
4	1,791.4	30.0	30.0	30.0
5	119.3	6.0	6.0	6.0
Total	3,985.7	130.8	130.8	130.8

[a] Total flow = 90,850 kg/h.

The dilution operation has two inputs and two outputs. The two inputs consist of the stream to be diluted and the dilution water. The two outputs are the diluted pulp stream and the excess dilution water. Flow from the second input stream is added to the first input stream to reach the desired consistency, which is specified by a parameter. This parameter specifies the consistency to which the slurry should be diluted. If the amount of available dilution water is not sufficient, the stream is diluted as completely as possible given the amount of dilution water. If the consistency of the pulp stream is already lower than the target consistency, no further dilution (and no thickening) occurs. (An example of the use of a dilution block as part of the primary stage of the forward cleaners is shown in Figure 6.)

Separation processes used in recycling include both screens and cleaners. Here we describe a unit operation that can be used to model both of these processes. In this operation, an input stream is split into two streams: an accepts stream, which ideally contains all the fibers and none of the contaminants, and a reject stream, which ideally contains all the contaminants. Since no separation process is 100% efficient, the efficiency for each division of each component must be specified. In this work, this is done by specifying the fraction of the flow of each component (as well as the total flow) that will leave in the accepts stream. (Note: see Figure 6 for an example of a system in which a separation operation is used for the centrifugal cleaner. The parameters are specified such that the denser and larger contaminants are more efficiently removed to the reject stream.)

The final operation is the continuously stirred tank reactor (CSTR), which is used in the pulping step (see Fig. 4). The CSTR is used as a surge tank to eliminate the variations in the flow from the pulper to produce a constant flow of stock to the rest of the system. The amount of material in the CSTR is caused by changes in the inflow while the outflow is constant.

PROCESS MODEL EXAMPLE

The example described in the following section is a recycling plant that receives 120 tons/day of wastepaper. The system is a boxboard recycling plant, and thus no deinking steps (washing or flotation) are performed. The paper as-received has 8% moisture content, 4.3% ash (dry basis), and 13% contaminants, which are divided into high density (heavy), neutral density, and low density (light) materials. Table II shows the flow rates of each component after pulping. Clean water is used for dilution. Future work will involve the recycling of whitewater from the thickening and water treatment steps back into the process.

Description of System

Figure 3 shows an overview of the process model for this recycling operation. The process takes the wastepaper through the steps of pulping, high density (HD) cleaning, screening, forward cleaning, reverse cleaning, and thickening to produce the cleaned pulp. In addition, the collected rejects and the water from the thickening step are sent to the water treatment operation to produce clarified whitewater and thickened rejects. In Figure 3, the thickening step is a single model block, that of a separation procedure, with removal efficiencies for each component. The mixers used to combine the rejects are likewise single operations.

The remaining blocks, such as the pulper and forward cleaners, are combinations of several basic operations. Thus, the modelling scheme allows the process model to be developed hierarchically and the process to be viewed at different levels of detail. Figure 4 shows the overview of the pulper block, which consists of four separate operations. The first step is the dilution of the wastepaper to the pulping consistency specified by the dilution block. The CSTR is a constant outflow tank that evens out the flow of pulp to the rest of the system. Overflow from the pulper is sent to the rejects. Larger contaminants are removed to the reject stream by extraction. The other two outputs of the entire pulper process are the CSTR states, which allow the user to monitor the amount of material in the tank, and the excess dilution water, which is sent to the next process.

The screening and two cleaning processes likewise consist of subprocesses. As an example, subprocesses involved in the forward cleaners are shown in Figure 5. The overall system has two inputs, the pulp feed and the dilution water, and three outputs, the cleaned pulp, rejects, and excess dilution water. The cleaners are arranged in a three-level cascade—the feed to the secondary cleaners consists of the rejects from the primary cleaners. The accepts from the secondary cleaners are returned to the feed of the primary cleaners. A similar relationship exists between the secondary and tertiary cleaners.

Figure 6 shows the basic operations involved in a single cleaning step, in this case, the primary stage. In the first step, the incoming pulp is mixed with the accepts from the subsequent stage. This material is then diluted to the proper consistency and sent to the cleaner for separation. The actual separation is performed by a separation block that has the removal efficiencies for each component as the parameters of the block.

Simulation Results

The process system was modelled and the results evaluated. The separation efficiency values for the operations were obtained from the literature (5,6,10,15,27). Figure 7 shows the flow of contaminants in the accepts streams after each cleaning operation.

The flows were divided into heavy contaminants (density greater than that of water), neutral contaminants (density approximately the same as that of water), and light contaminants (density less than that of water). The screening operation removed particles of all densities, which is to be expected since screens segregate primarily by particle size. However, the heavy contaminants

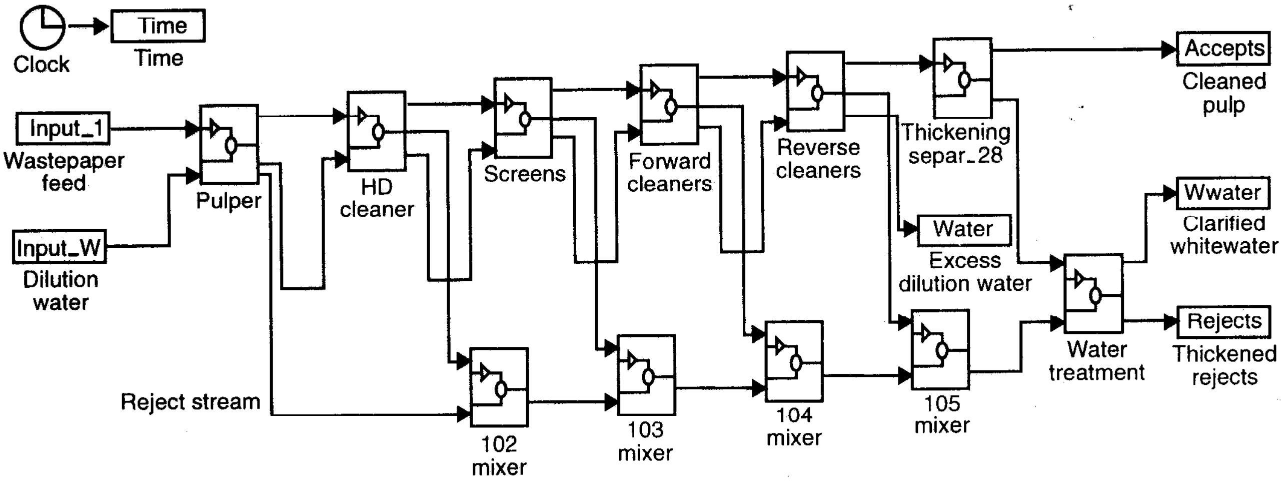

Fig. 3. Model of recycling system.

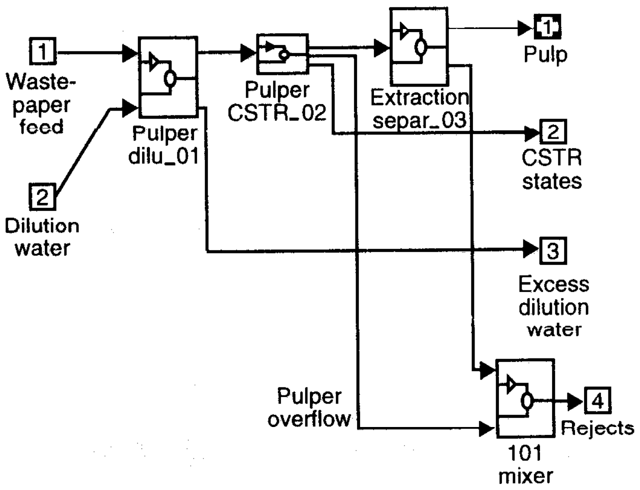

Fig. 4. Details of pulping process.

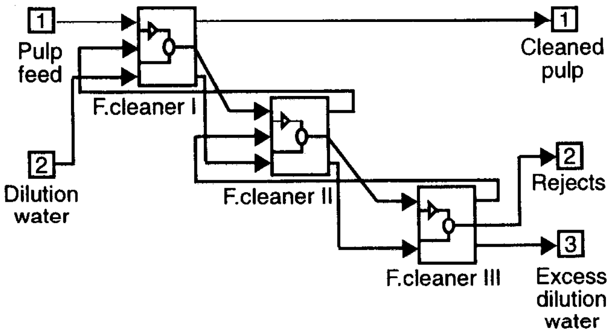

Fig. 5. Details of forward cleaning process.

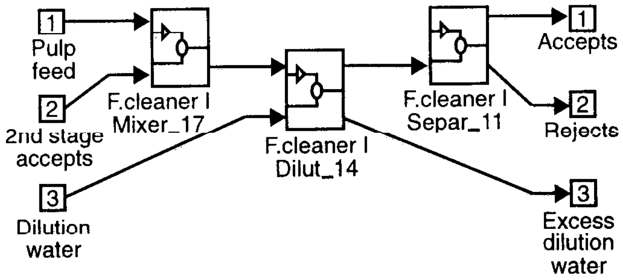

Fig. 6. Details of single forward cleaner.

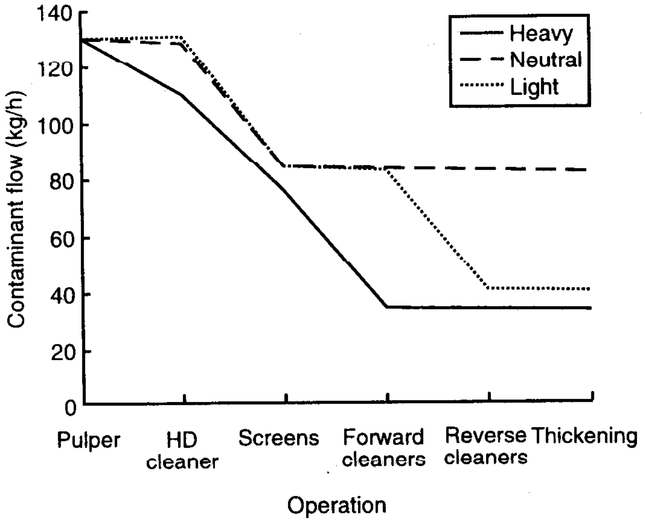

Fig. 7. Removal of contaminants based on density.

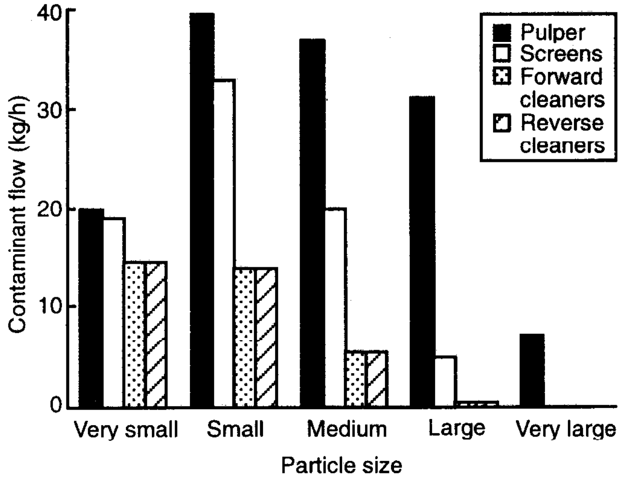

Fig. 8. Removal of contaminants based on size.

were removed more efficiently by the forward cleaners and the high density cleaner. The light contaminants were removed by the reverse cleaners. Those contaminants with approximately the same density of water that were not removed by the screens were very difficult to remove in the subsequent steps.

The effect of particle size on the efficiency of the forward cleaners was also modelled. Figure 8 shows the contaminant flows in the accepts streams for the heavy contaminants segregated by particle size. The largest particles were easily removed by the screens. The remaining large particles and the medium particles were removed with more than 75% efficiency. However, as the particle size decreased, the efficiency also decreased. The efficiency for removing very small particles was only 25%.

CONCLUSIONS

Modelling the size distributions of the flow of the components is important because the cleaning and screening efficiencies of the unit operations depend on these parameters. Modelling in this manner allows the systems to be designed to remove certain sizes of particles. The model can also be used to evaluate an existing process if the distribution of contaminants in the feedstock should change over time. The process design can be changed to improve the removal of particles of certain sizes that are "missed" in the current operation. In the future, stock preparation systems for recycled fiber will need to be able to efficiently handle a wide variety of feedstocks containing various types of contaminants. Finally, although not elaborated on in this report, fiber fractionation can also be model since the fibrous component is likewise treated as a distribution.

This work can be extended in several ways. First, our study was essentially conducted at steady-state conditions. The software and basic operations can also be used to dynamically model the process. This would allow the evaluation of the robustness of the stock preparation systems to upsets such as a "bad" batch of paper that is highly contaminated. It is desirable to design systems that quickly eliminate process upsets. Second, the parameters for the various operations were obtained from the literature, with some interpolation. In the future, operation parameters will be obtained from laboratory-scale and industrial operations. In doing this, the size classes can also be made more quantitative. Third, additional components, such as ink, can be included in the model. Inks can be distributed by particle size and possibly by hydrophobicity. Fourth, other recycling operations need to be considered, such as washing, flotation, dispersion, and agglomeration. Finally, it will be necessary to close the loop and use the recovered whitewater for dilution in the unit operations.

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