Lappeenranta University of Technology
Department of Chemical Technology

Disc Filter External Models in an Integrated Simulation Environment

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Foreword

This work was conducted as part of a Process Integration Parameter and Model Gallery project in co-operation with the System Dynamics Group of VTT Automation and laboratory of Process Systems Engineering of Lappeenranta University of Technology. The work was carried out at VTT Automation between January 2001 and March 2002.

I would like to thank my co-workers at VTT for valuable advice during the work. Marja Nappa and Jyrki Peltoniemi were my close advisers. My mentor Tommi Karhela has my gratitude because without his guidance the work would not have found its shape. I would also like to thank Markku Pitkänen from GL&V Finland for providing me with disc filter information and positive comments during the work. Petteri Luukkanen from GL&V helped to evaluate the model's accuracy. Without him the work would have been but a shadow of what it became.

Finally I would like to thank my fiancée Laura Saraste for her endless support, love and encouraging words throughout my thesis.

TIIVISTELMÄ

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Kemiantekniikan osasto

Tekijä: Marko Timo Mikael Mäkinen
Työn nimi: Kiekkosuodattimeen liittyvät ulkoiset mallit integroidussa simulointiympäristössä

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Hakusanat: kiekkosuodatin, dynaaminen simulointi, prosessi-integraatio
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Työssä tutkittiin kiekkosuodattimeen liittyviä ulkoisia simulointimalleja integroidussa simulointiympäristössä. Työn tarkoituksena oli parantaa olemassa olevaa mekanistista kiekkosuodatinmallia. Malli laadittiin dynaamiseen paperiteollisuuden tarpeisiin tehtyyn simulaattoriin (APMS), jossa olevaan alkuperäiseen mekanistiseen malliin tehtiin ulkoinen lisämalli, joka käyttää hyväkseen kiekkosuodatinvalmistajan mittaustuloksia. Laitetiedon saatavuutta suodattimien käyttäjille parannettiin luomalla Internetissä sijaitsevalle palvelimelle kiekkosuodattimen laitetietomäärittelyt. Suodatinvalmistaja voi palvella asiakkaitaan viemällä laitetiedot palvelimelle ja yhdistämällä laitetiedon simulointimalliin. Tämä on mahdollista Internetin ylitse käytettävän integroidun simulointiympäristön avulla, jonka on tarkoitus kokonaisvaltaisesti yhdistää simulointi ja prosessisuunnittelu. Suunnittelijalle tarjotaan työkalut, joilla dynaaminen simulointi, tasesimulointi ja kaavioiden piirtäminen onnistuu prosessilaitetiedon ollessa saatavilla. Nämä työkalut on tarkoitus toteuttaa projektissa nimeltä Galleria, jossa luodaan prosessimalli- ja laitetietopalvelin Internetiin. Gallerian käyttöliittymän avulla prosessisuunnittelija voi käyttää erilaisia simulointiohjelmistoja ja niihin luotuja valmiita malleja, sekä saada käsiinsä ajan tasalla olevaa laitetietoa. Ulkoinen kiekkosuodatinmalli laskee suodosvirtaamat ja suodosten pitoisuudet likaiselle, kirkkaalle ja superkirkkaalle suodokselle. Mallin syöttöparametrit ovat kiekkojen pyörimisnopeus, sisään tulevan syötön pitoisuus, suotautuvuus (freeness) ja säätöparametri, jolla säädetään likaisen ja kirkkaan suodoksen keskinäinen suhde. Suotautuvuus kertoo mistä massasta on kyse. Mitä suurempi suotautuvuus on, sitä paremmin massa suodattuu ja sitä puhtaampia suodokset yleensä ovat. Mallin parametrit viritettiin regressioanalyysillä ja valmistajan palautetta apuna käyttäen. Käyttäjä voi valita haluaako hän käyttää ulkoista vai alkuperäistä mallia. Alkuperäinen malli täytyy ensin alustaa antamalla sille nominaaliset toimintapisteet virtaamille ja pitoisuuksille tietyllä pyörimisnopeudella. Ulkoisen mallin yhtälöitä voi käyttää alkuperäisen mallin alustamiseen, jos alkuperäinen malli toimii ulkoista paremmin. Ulkoista mallia voi käyttää myös ilman simulointiohjelmaa Galleria-palvelimelta käsin. Käyttäjälle avautuu näin mahdollisuus tarkastella kiekkosuodattimien parametreja ja nähdä suotautumistulokset oman työasemansa ääreltä mistä tahansa, kunhan Internetyhteys on olemassa. Työn tuloksena kiekkosuodattimien laitetiedon saatavuus käyttäjille parani ja alkuperäisen simulointimallin rajoituksia ja puutteita vähennettiin.

ABSTRACT

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External models for rotary disc filters in an integrated simulation environment were studied in this work. The purpose of the work was to improve the accuracy of an existing disc filter model. The model was created into an dynamic simulation tool for the pulp and paper industry (APMS). The External model utilises measurement data and it can be used with an already existing mechanistical disc filter model. Availability of the disc filter parameters was enhanced by creating type definitions for filters in a server in the Internet. The filter manufacturer may export its equipment information into the server and combine it with simulation models for the equipment. This is enabled by an integrated simulation environment that comprehensively combines simulation, process design and the Internet. Dynamic simulation, steady state simulation and process diagram drawing can be made with one united toolset while process component data is available. These tools are to be implemented in a project called Gallery. A process model and component information database will be created into the Internet. A gallery user interface enables the designer to use different simulation tools, ready-made models and get up-to-date information on process equipment. The external disc filter model calculates drainages for different filtrates (cloudy, clear and super clear) and consistencies of the filtrates. Input parameters of the model are rotational speed, inlet consistency, freeness and angle of offset (determines the ratio between cloudy and clear filtrates). Freeness describes the mass that is being filtrated. Greater freeness means greater drainages and usually cleaner filtrates. The parameters of the model are tuned with regression analysis and by feedback from the manufacurer. The user may choose whether he wants to use the external model or the original model. The original model needs to be formatted by giving it nominal points for drainages and consistencies at certain rotational speed. The equations of the external model can be used in determining the nominal points should the original model give better results. The external model may also be used from the Gallery server without the simulation program. The user may also examine the disc filter parameters and see simulation results from his work station anywhere in the world, as long as there is a connection to the Internet. The work resulted in better availability for disc filter parameters and the shortcomings of the original model were diminished.

CONTENTS

List of Symbols

c	mass of particles deposited in the filter per unit volume of filtrate	, kg/m^3
c_{vat}	consistency in the vat	, kg/m^3
D_p	particle diameter	, m
k	permeability	, m^2
k_c	a coefficient that replaces 4.17 in Eq. (10b), (11) and (12)	, -
L	thickness L	, m
m_{av}	arithmetic average of the mass of solids in the cake	, kg
p	pressure	, Pa
p	pressure at thickness L	, Pa
p'	pressure at the boundary between the cake and the medium	, Pa
p_a	inlet pressure	, Pa
p_b	outlet pressure	, Pa
s	mass fraction of solids in the feed suspension	, -
s_p	surface area of a single particle	, m^2
u	velocity of filtrate	, m/s
u	volume flow rate per unit cross sectional area	, $m^3/(m^2\ s)$
w	mass of dry cake per unit area deposited within a distance z	, kg/m^2
V	volume of filtrate collected since the beginning of filtration until time t	, m^3
v_p	volume of a single particle	, m^3
z	thickness of the porous medium	, m
Δp	pressure drop across the cake and the filter	, Pa
Φ_s	shape factor or sphericity	, -
α	specific resistance	, m/kg
α_0	specific resistance at unit applied pressure, or at zero applied pressure	, $m/(kg\ kPa^n)$
α_{av}	specific resistance of the filter cake averaged over the compressive drag stress	, m/kg

ε	porosity, volume of voids per unit volume of cake or porous medium	, -
μ	viscosity of filtrate	, Pa s
ρ_s	density of solids	, kg/m^3

1 Introduction

1.1 Purpose of the Work

The purpose of this work was to improve an existing rotary disc filter simulation model and to increase availability of filter parameter information for process designers. The starting point was a dynamic simulation model that required knowledge of simulation results before the simulation could be started [1]. An external model was created for a simulation program that can be used with the original model in order to remove the need for addressing nominal points of operation in the model and to give flexibility and better resolution. External models can be used in an Advanced Paper and Pulp Mill Simulator (APMS) to create user-defined simulation models if the built-in models are not satisfactory. APMS is based on APROS (Advanced Process Simulator) developed by the Technical Research Centre of Finland in co-operation with an energy company Fortum. APROS is a dynamic simulator originally developed for power plant simulation and APMS is currently under development to become a comprehensive dynamic simulation tool for the pulp and paper industry.

1.2 Process Integration

Processes are becoming more and more complex as quality, efficiency, safety and environmental factors must be taken into consideration when building a production plant. Process integration sees the plant and its processes as one unit and tries to utilise all possible resources the most efficient way. This means basically reducing energy, raw material and water usage and increasing raw material and water recycling. The plant is not considered separate to its surroundings. Its effects on society and the environment are also taken into account. This approach is called process integration, which is defined by the International Energy Agency (IEA) as "Systematic and general methods for designing integrated production systems, ranging from individual processes to total sites, with special emphasis on the efficient use of energy and reducing environmental effects" [2]. This work was done as a part of a project that participates in the Process Integration Technology Programme for a Finnish Technology Agency[3].

1.2.1 Parameter and Model Gallery for Process Integration

Process designers nowadays have access to infinite amounts of information. Managing all the information has thus become increasingly important. Developing information management methods for designing, building, running and repairing processes is a part of the Process Integration Technology Programme [3]. The conventional definition of process integration (which is a much narrower concept concerning mostly just energy integration) is therefore broadened to include information management as well.

The more information available on equipment the better the choices that can be made when choosing process components. Simulating often requires detailed information on the component in hand. This information is often difficult to find and the information can be inaccurate or ambiguous. Process simulation is steadily increasing in importance and the accuracy of the simulation model is strongly dependent on the process component parameters fed to the model. Parameter and Model Gallery for Process Integration (Gallery for short) is a project that aims to improve availability of component configuration data for simulator users and plant designers. Several process component manufacturers are participating in the project and they provide data on their products in the database.

Manufacturers have freedom to decide what kind of data they want to put into the Gallery. They can put just essential information, or upload their entire product database into it. The data model in the Gallery is extremely flexible. A pump manufacturer, for example, can put just their basic pump types and their characteristic parameters (dimensions, rotational speeds, min/max capacities and heads) into the Gallery, or they can put as detailed information as they want, like characteristic pump curves for various process conditions, dimensional drawings, exploded views of pumps etc.

Gallery is also a model database. It contains ready made simulation models that can be reutilised by designers. Simulation models are often made from scratch and when someone does the same work someone else has already done, time, effort, work and money are often wasted. From an educational point of view repeating things can be beneficial, but the Gallery tries to diminish the need for unnecessary work.

1.2.2 Gallery and the Integrated Simulation Environment

The aim of the Gallery project is also to establish a modern design environment for process designers that would seamlessly integrate computer aided process design and simulation [4]. Work with a design problem is more efficient if pipeline design, process control system design, equipment choosing and simulation go hand in hand.

Traditionally a process designer first carries out spreadsheet calculations to get an initial idea of mass flows and balances. After that static simulation programs are used as aids for process equipment dimensioning. The designer then goes through several - possibly out of date - catalogues and requests offers from the component manufacturers. Process control design is done at basic level, often relying heavily on the designer's expertise. Final tuning of the controls is made when the plant is running. Transient behaviour of the process can be only evaluated by the designer's insight. Hazards and exceptional conditions are not efficiently and comprehensively researched within the possibilities of modern dynamic simulators. Traditional process design is sequential which is time consuming.

In the integrated simulation environment dynamic simulation should be used throughout the design process. It is a modern way of developing new processes and analysing the existing ones. Control systems can be reliably modelled and tested throughout the design process. Gallery provides up to date information on process components. Special equipment can be simulated by using external models that are also found in the Gallery. Detailed information of transients, hazards and exceptional conditions can be attained. Operator training is possible throughout the project.

Process design in the integrated simulation environment is an example of concurrent design. It is essential from an efficiency point of view that all design events that can be engaged simultaneously are, in fact, engaged simultaneously. There is however a strong tradition of sequential design in the process industry. Dynamic simulation tools are not nearly as widely used as steady state simulators. For dynamic models more information is needed since there is an extra dimension (time) in the calculations. The models also become more complex than steady state ones and require extra computational resources.

The quicker an engineer adopts a more concurrent engineering style, the faster he gains an advantage over traditional sequential designers. Reducing the total design time with concurrent engineering tools does not mean making things more hastily. For example, instead of spending a month doing one thing and another month doing another the designer can use one and a half months doing two things concurrently and there is no need to go back and correct the errors made in the first half of the design period. Process design and process control design is a good example of two design tasks that should always go hand in hand aided by dynamic simulation.

1.2.3 Disc Filter Simulation and Information in the Gallery

The external rotary disc filter model can be used with or without a simulation program in the Gallery environment. Data definitions for different disc filter types were created into the Gallery server. Disc filter manufacturers can import information about their products into it and the process designers can then retrieve information concerning disc filters from the Gallery. The manufacturers can control how much and how detailed the information they want to give to their customers. Since the manufacturer not only provides the technical specifications of the device, but also a simulation model of the component, the designer can immediately see how the device would work in practice. The external model mechanism can be included into any process component that is in the Gallery thus allowing a comprehensive examination of the desired process components before choosing any.

The original disc filter model is based on mechanistic models. The model creator suggested that further study should be made on how the model could utilise measurement data for more case specific simulation. Mechanistic models are common and usually preferable. They can be examined by studying the theory behind them.

Judgement of validity can be made even before testing whether the model is consistent with real life results. Mechanistic models tend to be very general, but still they often require parameter values based on measurements. This work concentrated on making a model that utilises measurement data provided by the manufacturer. This would provide case-specific simulation results for certain devices, production type etc.

The original disc filter simulation model may utilise the external model during the simulation run. This enables more accurate calculations than the basic simulation model, since individual filter characteristics and process conditions can be taken into account when running the simulation. The mechanistic approach should be formatted with (possibly guessed) simulation results before starting. The external model can also be turned off so the model uses only the original mechanistic model and the mechanistic model can be initialised with the results of the external model. The external model uses equations derived from measurement data to evaluate filtrate flows and consistencies. Its inputs are rotational speed, freeness, inlet consistency and angle of offset (determines the ratio between cloudy and clear filtrates). Outputs are filtrate flows (of cloudy, clear and super clear) and the consistencies of the filtrates, respectively. Other calculations like pulp production, disc washing, overflow simulation etc. are still calculated by the original model.

2 Filtration

Separation is an important field in process industry. Filtration is one of the most common mechanical separation processes. In many cases the desired product is within a mixture of raw materials, reagents, impurities like oil from compressors, catalysts etc. The product must be separated efficiently from this mixture. Recovering valuable solids from the liquid is probably the most usual case of filtration, although the recovery of liquid (solids being discarded) and the recovery of both liquid and solids are also very common.

Separation processes also have a big role in wastewater treatment. In this case neither solids nor liquid necessarily need to be recovered, but they must be separated so that clean water can be discharged and solids can be processed further.

Closing water cycles in paper mills requires efficient separation techniques because wastewater is being reused inside the mills after purification. In a closed system problems can develop quite easily because the constant feed of fresh material to the system contains all kinds of impurities that accumulate in the water cycles and may render the paper machine into an unwanted state. With modern control systems, measurements and separation equipment the need for fresh water (and hence wastewater production) is reduced and environmental load is diminished.

There are two main categories of filtration processes: diffusional and mechanical separation. In diffusional separation, mass transfer takes place between different phases. Mechanical separation techniques are based on differences in physical properties of the separable materials, such as density, size or shape.

Mechanical separation is most commonly executed with either a separating membrane or by sedimentation. The membrane allows one or more components to pass and retains the others. If the components are separable with sedimentation, no membrane is needed. Sedimentation is an effective separation method only if physical differences such as density and solubility between components are favourable.

A driving force is needed in both cases. With a membrane there has to be a pressure difference across it. An overpressure on one side or a vacuum on the other are the most common cases. Also gravity can operate as a driving force. Sedimentation requires no membrane and therefore it takes place under constant pressure. Gravity or centrifugal force separates the components.

Filtration can be continuous or discontinuous. The division is made based on whether the discharge of solids is continuous or intermittent. Mechanical filters are furthermore divided into cake, clarifying and crossflow filters [5].

2.1 Basic Filter Types

2.1.1 Cake filters

At the start of filtration, cake filters have only a filtration medium between the feed and filtrate. Some particles of the feed are carried into the pores of the filtering medium and they become immobilised. Soon particles begin to collect onto the surface of the medium. As the cake on the surface thickens, it too starts to filter and the effect of the medium will become negligible.

2.1.2 Clarifying filters

Clarifying filters remove small amounts of solids from the feed to produce clean gases or sparkling clear liquids such as beverages. The pores of a clarifying filter are much larger than the diameter of particles to be removed. The solid particles are trapped inside the pores or on its external surfaces. Clarifying filters must be regenerated regularly because the impurities build up in the filters. The regeneration is commonly executed with hot steam that flows through the filter.

2.1.3 Crossflow filters

Feed suspension of a crossflow filter flows under pressure at fairly high velocity across the filter medium. Cake formation is mostly prevented because of shear force operating on the medium. The medium withholds most of the particles and clear filtrate (containing some smaller particles) passes through the medium.

2.2 Cake Filtration Theory

2.2.1 Principles of Filtration

Darcy's law can be written as

$$u = \frac{-k}{\mu}\frac{dp}{dz} \tag{1}$$

where
where	k	permeability
	p	pressure
	u	volume flow rate per unit cross sectional area
	z	thickness of porous medium
	μ	viscosity

Equation (1) was developed by Darcy in 1855. He carried out a series of measurements involving the flow of water through a bed of sand placed in a vertical iron pipe. Darcy did not include viscosity in his equation so (1) is the customary form of his equation used today [6, p. 16].

Darcy's law of filtration is usually presented in a modified form. Permeability is replaced by specific resistance and the pressure gradient (*dp*/*dz*) is replaced by the pressure loss per unit mass of solid deposited on the medium.

$$u = -\frac{1}{\mu\alpha}\frac{dp}{dw} \tag{2}$$

where	w	mass of dry cake per unit area deposited within distance z
	α	specific resistance

dw and *dz* are related by:

$$dw = \rho_s (1-\varepsilon)\, dz \tag{3}$$

where ε porosity, volume of voids per unit volume of cake or porous medium

ρ_s density of solids

k and α are related by:

$$k = \frac{1}{\rho_s (1-\varepsilon)\alpha} \tag{4}$$

Equations (2)-(4) are from Wakeman and Tarleton [6, p. 17].

2.2.2 Cake Filtration

If flow resistance is not constant, but a cake is built up on the surface of the medium, a different approach is needed for the filtration calculation. Cake formation increases pressure drop across the filter and reduces the flow of filtrate. If the pressure is kept constant, filtration is called *constant pressure filtration*. If the pressure is increased so that the filtrate flow remains constant, filtration is called *constant rate filtration*.

2.2.3 Pressure drop through the filter cake

Figure 1 shows the profile of the pressure drop across the cake and the filter at time t from the start of the filtration. At the beginning of filtration there is no cake and its resistance is zero. The pressure drop is

$$\Delta p = p_{\mathrm{a}} - p_{\mathrm{b}} = (p_{\mathrm{a}} - p') - (p' - p_{\mathrm{b}}) = \Delta p_{\mathrm{c}} - \Delta p_{\mathrm{m}} \tag{5}$$

where p_{a} inlet pressure

p_{b} outlet pressure

p' pressure at the boundary between the cake and medium

Δp pressure drop across the cake and the filter

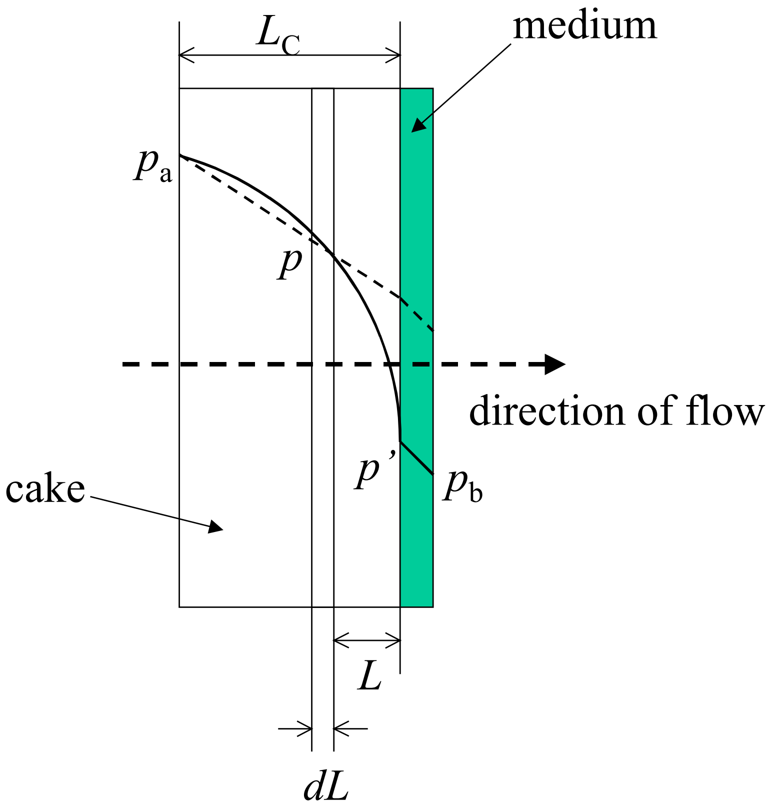

Figure 1. A section through a filter medium and cake, showing pressure gradients; p, fluid pressure; L, distance from filter medium. The dashed line represents the pressure drop in an in-compressible cake and the continuous line represents pressure drop in a compressible cake.

Kozeny-Karman equation presents the pressure gradient across a cake of thickness L [5, p. 1016]

$$\frac{dp}{dL} = \frac{150\mu\, u\,(1-\varepsilon)^2}{(\Phi_s D_p)^2\,\varepsilon^3} \tag{6}$$

where	L	thickness L
	p	pressure at thickness L
	u	velocity of filtrate
	μ	viscosity of filtrate
	ε	porosity of cake
	D_p	particle diameter
	Φ_s	shape factor or sphericity

Often the pressure drop is expressed as a function of the surface-volume ratio instead of the particle diameter and shape factor. By substituting $\Phi_s\, D_p$ with $6(v_p/s_p)$, Equation (6) gives:

$$\frac{dp}{dL} = \frac{4.17\mu\, u\,(1-\varepsilon)^2 \left(\frac{s_p}{v_p}\right)^2}{\varepsilon^3} \tag{7}$$

where	s_p	surface area of a single particle
	v_p	volume of a single particle

If the particles in the cake are compressible or if the void fraction is very low, the coefficient 4.17 in Equation (7) can be much higher.

The superficial velocity is:

$$u = \frac{dV/dt}{A} \tag{8}$$

where V volume of filtrate collected from the beginning of filtration until time t

The volume of solids in the layer dL is $A(1\text{-}\varepsilon)dL$. The mass of solids is calculated by multiplying the volume by the density of the solids ρ_p

$$dm = \rho_\mathrm{p}(1-\varepsilon)AdL \tag{9}$$

Eliminating dL from Equations (7) and (9) yields

$$dp = \frac{4.17\mu\, u\,(1-\varepsilon)\left(\frac{s_\mathrm{p}}{v_\mathrm{p}}\right)^2}{\rho_\mathrm{p} A \varepsilon^3} dm \tag{10}$$

2.2.4 Incompressible Cakes

If the filtered particles are rigid, the cake is incompressible and all factors on the right side (except m) in Equation (10) are independent of L and the equation can be integrated directly [5, p. 1018]

$$\int_{p'}^{p_\mathrm{a}} dp = \frac{k_\mathrm{c}\mu\, u\,(1-\varepsilon)\left(\frac{s_\mathrm{p}}{v_\mathrm{p}}\right)^2}{\rho_\mathrm{p} A \varepsilon^3} \int_0^{m_\mathrm{c}} dm \tag{10b}$$

where k_c a coefficient that replaces 4.17 in Eq. (10)

$$p_{\mathrm{a}} - p' = \frac{k_{\mathrm{c}} \mu\, u \left(1-\varepsilon\right) \left(\dfrac{s_{\mathrm{p}}}{v_{\mathrm{p}}}\right)^2 m_{\mathrm{c}}}{\rho_{\mathrm{p}} A \varepsilon^3} = \Delta p_{\mathrm{c}} \tag{11}$$

The specific cake resistance is defined by [5, p. 1018]

$$\alpha = \frac{\Delta p_{\mathrm{c}} A}{\mu\, u\, m_{\mathrm{c}}} = \frac{k_{\mathrm{c}} \left(1-\varepsilon\right) \left(\dfrac{s_{\mathrm{p}}}{v_{\mathrm{p}}}\right)^2}{\rho_{\mathrm{p}} \varepsilon^3} \tag{12}$$

2.2.5 Filter Medium Resistance

Filter medium resistance is [5, p. 1018]

$$R_{\mathrm{m}} = \frac{\left(p' - p_{\mathrm{b}}\right)}{\mu\, u} = \frac{\Delta p_{\mathrm{m}}}{\mu\, u} \tag{13}$$

Solving Δp_{c} from Eq. (12) and Δp_{m} from Eq. (13) yields

$$\Delta p = \Delta p_{\mathrm{c}} + \Delta p_{\mathrm{m}} = \mu\, u \left(\frac{m_{\mathrm{c}} \alpha}{A} + R_{\mathrm{m}}\right) \tag{14}$$

In Eq. (14), it is not convenient to use the linear velocity u and the mass of solids in the cake m_{c}. The total volume of filtrate collected in time t replaces them. The mass of solids and the total volume are related by

$$m_{\mathrm{c}} = Vc \tag{15}$$

where c mass of particles deposited in the filter per unit volume of filtrate

Substituting u in Eq. (14) with the right hand side of Eq. (8) and m_c with the right hand side of Eq. (15) gives

$$\frac{dt}{dV} = \frac{\mu}{A(\Delta p)}\left(\frac{\alpha c V}{A} + R_\mathrm{m}\right) \tag{16}$$

2.2.6 Compressible Cakes

In reality, most cakes are not incompressible, but compressible. In a compressible cake the material near the medium is more tightly packed. Pressure loss increases near the surface of the medium. If the cake is compressible, Eq. (16) must be modified. Wakeman *et al.* [6p. 63] propose the following equation for compressible cakes

$$\frac{1}{A}\frac{dV}{dt} = \frac{A(\Delta p)}{\mu(\alpha_\mathrm{av} c V + A R_\mathrm{m})} \tag{17}$$

where α_av specific resistance of the filter cake averaged over the compressive drag stress

Modifying Eq. (17) to a similar form as (16) gives

$$\frac{dt}{dV} = \frac{\mu}{A(\Delta p)}\left(\frac{\alpha_\mathrm{av} c V}{A} + R_\mathrm{m}\right) \tag{18}$$

in which [6p. 63]

$$c = \frac{\rho_\mathrm{l}\, s}{1 - m_\mathrm{av} s} \tag{19}$$

where m_av arithmetic average of the mass of solids in the cake

s mass fraction of solids in the feed suspension

$$\alpha_{\mathrm{av}} = \alpha_0 \left(1-n\right) \Delta p_{\mathrm{c}}^{\mathrm{n}} \tag{20}$$

where α_0 specific resistance at unit applied pressure, or at zero applied pressure

3 Rotary Disc Filter

Rotary disc filters are used for large scale separation of relatively free filtering suspensions, where washing is not required. Kovasin [7] states, that they are the most commonly used filters for mechanical pulp precipitation. Another big user of disc filters is the mining industry where ore is removed from water with them. According to Wakeman *et al.* [6 p. 212], the filters usually operate well for particle sizes 1-700 µm and concentrations of 3-30 volume-%.

3.1 Construction of the rotary disc filter

A schematic picture of a rotary disc filter is presented in Figure 2.

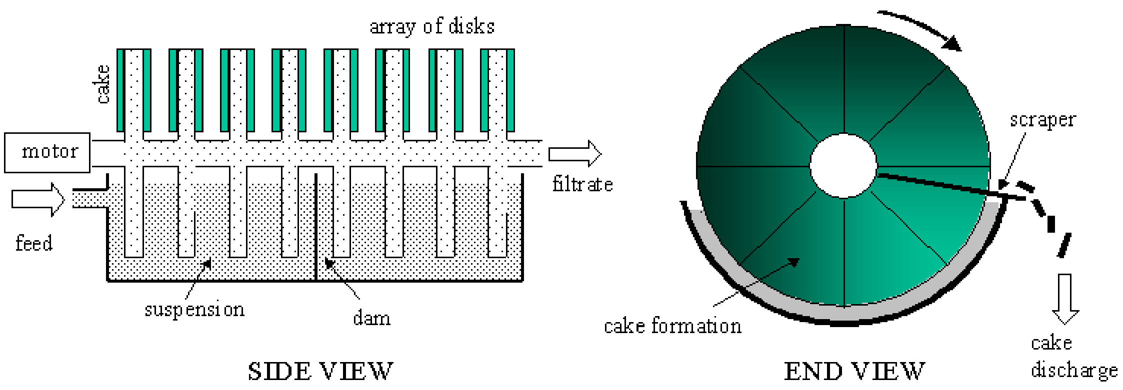

Figure 2 Side and end views of a rotary disc vacuum filter, as presented by Wakeman *et al.* [6 p. 212].

Traditional units comprise of up to 12 flat, circular discs rotating on a central horizontal shaft. The biggest units that GL&V manufactures can have up to 30 discs. The discs are hollow, sectored and covered with a filter cloth. There are usually 20 sectors per disc [7]. Göttsching and Pakarinen [8, p. 173] state that the disc filter may have up to 34 discs 3.0-5.5 m in diameter and the total length of the unit can be 12 m. The discs rotate at about 0.5-2 rpm.

Rotary disc filters have inherently large filtration areas compared to the used floor space. Wakeman *et al.* [6 p. 212] state that the total cloth area can be between 0.05-300 m^2.

There are also ceramic disc filters. In ceramic filters the filtration cloth and supporting porous plates are replaced with sintered alumina membranes with nearly uniform pores. They are mechanically more durable than conventional filters. Since there is no filtering cloth (the ceramic structure serves as both filtering and supporting structure), the replacement of a filtration medium can be very expensive. The ceramic medium is much more wear resistant than conventional filtering cloths but the pores in ceramic filters must be cleaned regularly in order to maintain operability. This is usually done by backflushing them with filtrate. Further cleaning can be done by applying ultrasound. Ceramic filters have filter areas up to 45 m^2.

There is a special case of disc filter construction developed by GL&V. The major difference between normal and rotor design is that the rotor version lacks a central shaft. This enables a greater degree of disc submergence into the slurry and increases capacity. The pulp is dropped into the centre trough and conveyed away with a screw.

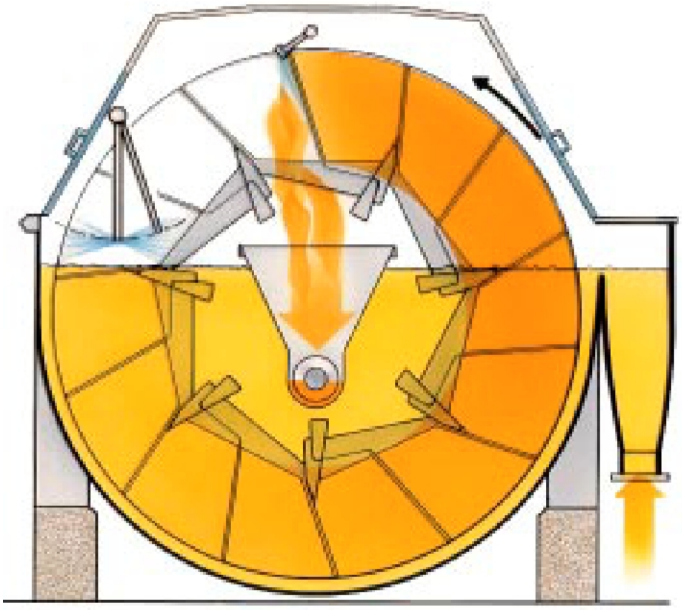

Figure 3 A picture of Celleco Centerdisc CDI. Notice that there is no central shaft as in traditional disc filter models. Pulp is gathered into the central trough. Filtrates are gathered through channels of the "spider" in the centre.

3.2 Operation of the filter

As the discs rotate, they pass through individual stirred tanks containing the feed suspensions. Vacua applied inside the discs cause cake formation on the surface of the filtering cloths. According to Göttsching and Pakarinen [8, p. 173] the discs are usually immersed about halfway into the slurry. As the sector that has cake on its surface emerges from the slurry, it can be dried by sucking air through it. The cake is removed from both sides of the disc with scrapers or water sprays. This can be aided with air blown through the sector. Cake washing is virtually impossible due to vertical cake formation.

The disc filter cycle is represented in Figure 4.

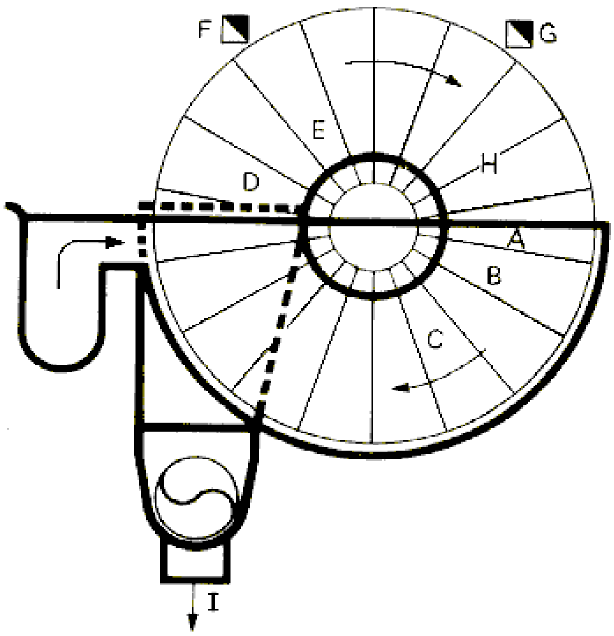

Figure 4. The disc filter cycle: (A) sector begins to gravity-fill core outward; (B) vacuum on, cloudy filtrate collected; (C) clear filtrate obtained; (D) vacuum off; (E) atmospheric port opens; (F) knock-off shower peels mat; (G) wire washing starts; (H) atmospheric port closes; (I) thickened pulp discharged. Smook, G.A. and Kocurek, M.J. [9, p. 228]

3.3 Rotary Disc Filter Placement in a Papermill

In papermills rotary disc filters are used for fibre recovery from white water. They are in the secondary water circuit which circulates fibre rich white water from the wire section of the paper machine. Disc filter save-all has a dual function: it recovers fibre for the papermaking process as well as purifying water for re-use. Figure 5 shows a sketch of the process near the disc filter.

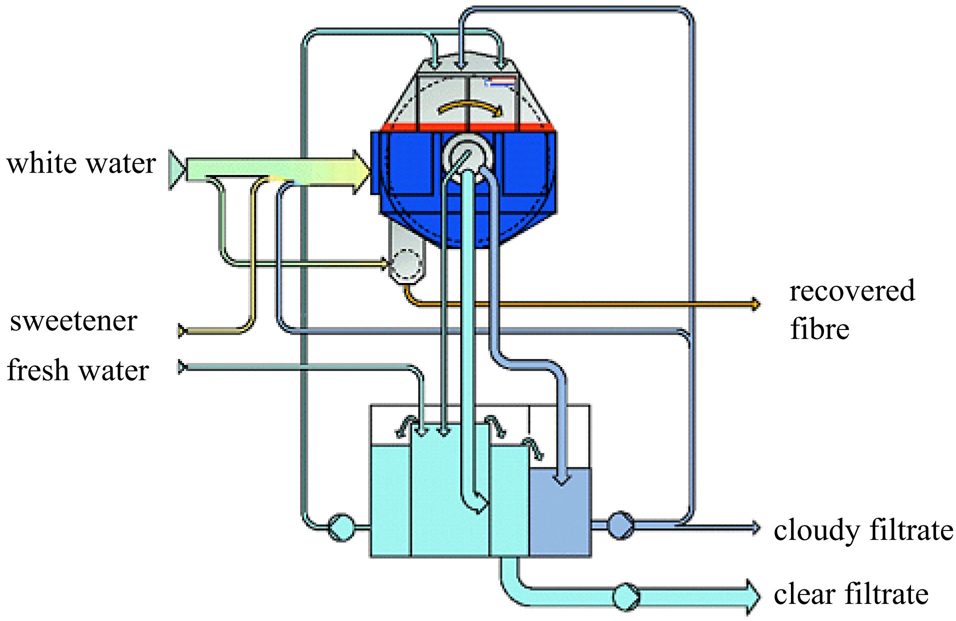

Figure 5. A rotary disc filter process in a paper mill [10].

Typical process surrounding a disc filter in a papermill is shown in Figure 6.

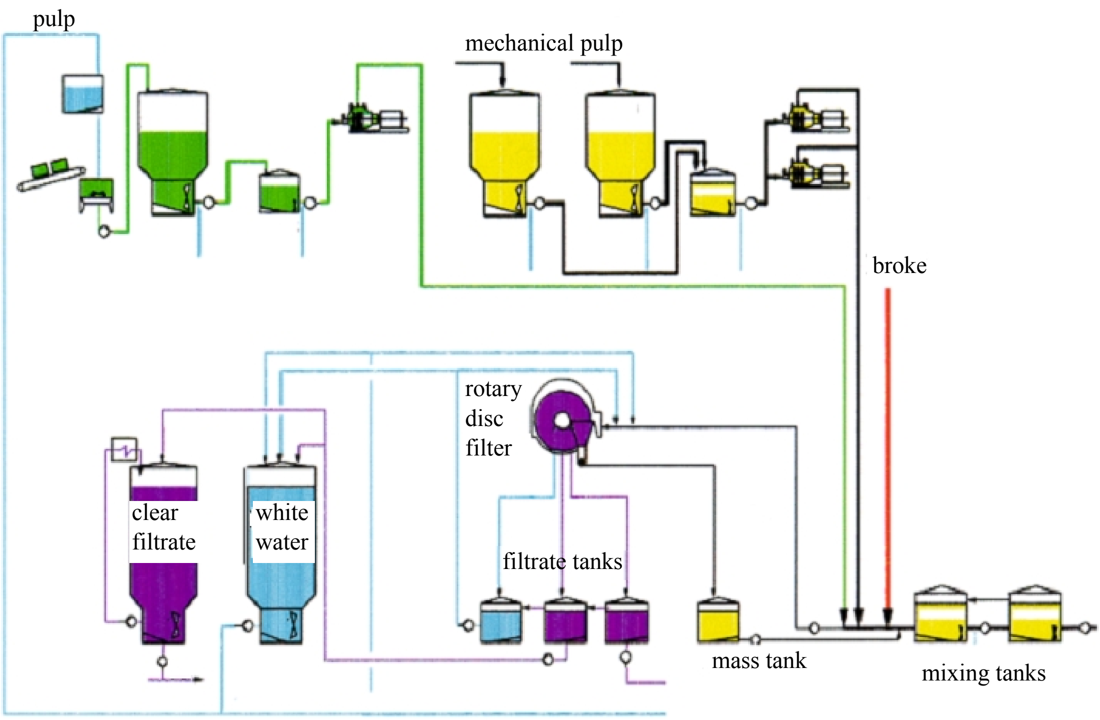

Figure 6. Paper mill process surrounding a rotary disc filter [10].

3.4 Masses Filtrated with a Disc Filter in the Paper Mill

3.4.1 White Water

In a papermill the secondary water cycle circulates water that is removed from the pulp at the wire. The water contains solids and dissolved material. It is called white water because of its colour. Solids are mainly fibres and ashes such as fillers or pigments that penetrate the wire and are left in the wire water. There are also paper process additives in the water that should be removed if clean water is desired.

Fibres are the biggest and most easily departed impurities in white water. Disc filters are used in order to make both the water and fibre reusable in paper mill processes. If the filter works well, it produces water clean enough for paper machine showers and other use in the mill. The pulp that is collected from the filter has apprehended much of the ashes.

To some degree ultra- and even nanofiltration are used to remove the smaller impurities and dissolved material from the disc filter filtrates. These technologies are needed more and more in the future, because there is an evermore increasing pressure to make paper mills more environmentally friendly.

3.4.2 Sweetener

White water contains very little fibre but lots of ash. Since the disc filter is a cake filter device, white water itself does not generate a cake and filtration can be very inefficient. Fibre must be added to the disc filter feed to ensure functionality. Ash can be removed with modern techniques like ultrafiltration, but pressure loss and energy demand are far greater than with disc filters. An even bigger problem is the small capacity and membrane fouling. The solution to complete wire water ash removal is therefore uneconomical and there is still a problem with what to do with the filtered ash.

Basically the disc filter is nothing more than a machine that tries to return as much of the rejected material as possible back into the paper machine. Disc filters leave some ash in the filtrate, but they also bind some of the ash in the reused pulp.

The sweetener stream is added to the filter feed so that the consistency of feed stays between 0.5-1.0 %. There is typically 2-5 grams of sweetener for every gram of solid in white water. A considerable amount, over 10 %, of the paper machine’s feed pulp circulates as filter aids for the disc filters.

The sweetener can be different types of pulp like TMP or CTMP or it can be broke etc. Each sweetener gives the filter different filtration characteristics. The most important feature of the sweetener is its freeness as far as disc filter operability is concerned. Freeness describes how well the mass lets water pass through and it also determines how clean the filtrates are. Typically freeness changes between 30-700 ml CSF. CSF stands for Canadian Standard Freeness, which is the standardised test for measuring freeness.

If freeness number is very big, water penetrates the mass cake easily. The freeness number decreases if the degree of beating increases. A mass that has a low beating rate contains more robust bigger fibres that form an easily penetrable cake. Mass with a strong beating have short and broken fibres that form a dense cake and render the filtrates less clean. A rough classification of typical sweetener freenesses for different types of paper mill production is presented in Table I [11].

Table I Typical sweetener freenesses of different paper mill production types.

Canadian Freeness (CSF), ml	Type of Production
30	super calendered (SC)
50	light/middle weight coated paper (LWC or MWC)
100	news print
200-400	board
500-600	fine paper
700	recycled paperboard like old corrugated container (OCC)

The disc filter is said to be the disturbance generator of a paper mill. It is a relatively simple machine, but since it brings reject from the wire back into the paper machine, it can potentially mess up the whole process if the filtration is not executed properly. Fluctuations in the consistency and composition of the feed of the paper machine must be kept minimal. Hence the sweetener plays a major role, because it determines much of how the cake is formed on the discs and how the filter behaves.

3.5 The filtrates

The filter cycle produces two or three different filtrates: cloudy, clear and super clear. Cloudy filtrate is obtained when the sector first enters the slurry. There is no cake on the surface of the cloth and a lot of fibre passes through the filter medium. Cloudy filtrate contains 100-600 mg/dm^3 of solids. As the disc rotates further, fibre cake formed on the medium increases the pressure loss of the filter and less filtrate is passed through. The filtrate is also clearer than without the cake. Clear filtrate has a solids content of approximately 20-200 mg/dm^3. Before the disc emerges from the slurry, the cake has thickened and compressed, and the obtained filtrate is called super clear. It's solids content is between 5-50 mg/dm^3. There are filters that collect only two types of filtrates, cloudy and clear. The yield of super clear filtrate is usually very small compared to cloudy and clear filtrates and therefore it is not collected in every device.

Filtration starts first due to a hydrostatic head difference between suspension level and filtrate level. If the vacuum is applied too early, a dense cake forms quickly on the filtering medium and filtrate flow is blocked by the cake. Therefore gravity is first used as a driving force and then a vacuum is applied. Göttsching and Pakarinen state [8, p. 174] that the vacuum is usually about 0.75-0.5 bar absolute pressure. A vacuum is customarily created with a drop leg and it is directly proportional to the length of the leg. Different filtrates may have different drop leg lengths and the diameters of the legs may also vary.

4 Process Simulators

4.1 Simulators in Process Engineering

The use of process simulation has been steadily increasing. Computational power has increased dramatically while computer prices have been decreasing. This has made simulation a very economical way to design and analyse processes. Chemical engineering problems need to be examined more and more comprehensively, and simulation gives the tools to handle this trend. There are many potential hazards involved with a chemical process plant. Simulation is often the only safe and cost-effective way to analyse such events. Modernisation and optimisation of already existing plants and processes is also an important area of process simulation.

The simulation’s restrictions become evident when simulating more complex unit processes. Reactors for example are often very difficult to simulate. Some physical laws governing the reactions can be unknown in unexpected process conditions and that removes much of the simulation benefits. Simulation programs tend to be “general”. They do not include any specific simulation models for special equipment. Therefore many simulation programs implement the possibility for the user to build such models themselves.

There are two basic kinds of simulators; steady state and dynamic. A few common simulators of both types are presented in the next chapters. There is a more detailed description of APMS, since the external model was created into it.

4.2 Steady State Simulators

Steady state simulators are well suited for mass and energy balance calculations. They are normally tools for initial design, although very complex existing processes can also be modelled with them. It is not possible to do process control engineering with steady state simulators, since they can not calculate transient behaviour.

Aspen Plus by Aspentech is a widely used steady state simulator. It supports all major computer and operating systems and it can be used with a graphical user interface. Aspen Plus can be used to model petroleum refining, nonideal chemical systems and processes containing electrolytes and solids. Aspentech announces, that their customers use Aspen Plus for research and development of process, engineering and production [12].

Pro/II by Simulation Sciences Inc. is a steady state simulator for material and energy balance calculations. According to Simulation Sciences [13] it can be used for

- designing new processes
- evaluating alternate plant configurations
- modernising and revamping existing plants
- assessing and documenting compliance with environmental regulations
- troubleshooting and debottlenecking plant processes
- optimising and improving plant yields and profitability

CHEMCAD is process simulation software made by Chemstations. They say [14] that it can be used in modelling

- distillations/extractions (batch & continuous)
- reactions (batch & continuous)
- electrolytic processes
- thermo-physical property calculations
- vapour/liquid/liquid equilibrium calculations
- equipment sizing
- heat exchanger networks
- environmental calculations
- safety analyses
- cost estimations
- flare header systems
- utility networks

Users can add their own unit operations, thermodynamic components and graphic symbols to the program.

4.3 Dynamic Simulators

Dynamic simulators are capable of performing time-dependant analysis on processes. They calculate how the process and its controls respond to various upsets as a function of time. Dynamic simulation can be used to evaluate equipment configurations and control schemes and to determine a design's reliability and safety before a significant amount of capital is committed to the project. It is possible to analyse transient conditions and plant startup and shutdown sequences with a time dependant simulator. Dynamic simulators are therefore extremely useful for operator training, control tuning and safety analysis [15].

It is not an understatement to say that not very many process designers have yet opened the time dimension in their simulation models. In the right hands a mass and energy balance model built into a very affordable spreadsheet program can give very reliable results. It requires very little resources from hardware and software. Dynamic simulation used to require expensive Unix mainframes and extensive expertise. Personal computers have today become so fast and their memory reserves so ample that a dynamic simulation model can now be built into a computer that can be purchased by any engineer. More and more user-friendly interfaces are built. Computers will not become slower and dynamic simulation will not become more difficult or costly to use in the future, quite the opposite.

Dynamic simulators are still rare and more expensive than steady state simulators and they are somewhat more difficult to use. Process designers are not necessarily content with the simulation software on the market today. Universities teach dynamic simulation to a lesser degree. Dynamic approach is still new technology compared to steady state balance calculations that every chemical engineer has done, but it is the technology that will inevitably become widely used.

Hyprotech has a dynamic process simulator called HYSYS. It is a product family that has tools intended for plant design, process flowsheeting, case studies, controller design, operator training and distillation equipment modelling. There are also HYSYS-products specialised in refineries and ammonia plants.

DYNAPLUS is a dynamic simulation tool by Aspentech. It is an interface between the ASPEN PLUS and SPEEDUP. ASPENPLUS performs steady state calculations of energy and material balances and SPEEDUP carries out the dynamic simulation. The system works so that ASPENPLUS solves the material and energy balances one process unit at a time, while SPEEDUP simultaneously carries out the solution of differential and algebraic equations of the whole flowsheet. DYNAPLUS converts the equations and specifications from one architecture to another [16, p. 778].

4.4 APROS/APMS

APROS/APMS (Advanced PROcess Simulator/Advanced Paper Mill Simulator) is a general purpose simulation environment with a graphical user interface and tools for model development. It has been developed by the Technical Research Centre of Finland. APROS can be used during both process design and analysis of a ready plant. APROS was originally intended for conventional and nuclear power plant simulations. APMS was designed later to meet the simulation needs of the pulp and paper industry.

Nowadays the APROS/APMS simulation environment is designed to cover a broad range of simulation applications. In its largest version, APROS/APMS serves as a tool for developing new models and solution algorithms for any process, which can be described using the APROS/APMS database structures. APROS/APMS can be used for operator training, process and automation design, plant analysis and automation testing.

The simulation model can be built by using a command line editor or a graphical interface called GRADES. A model consists of modules that represent process components. Components are for example valves, pipes, tanks, heat exchangers, controllers and pumps. Components are defined in an input form that consists of component parameters. Then the components are linked together. Automation components are added to the model after all the components are defined. Figure 7 shows a picture of a GRADES interface.

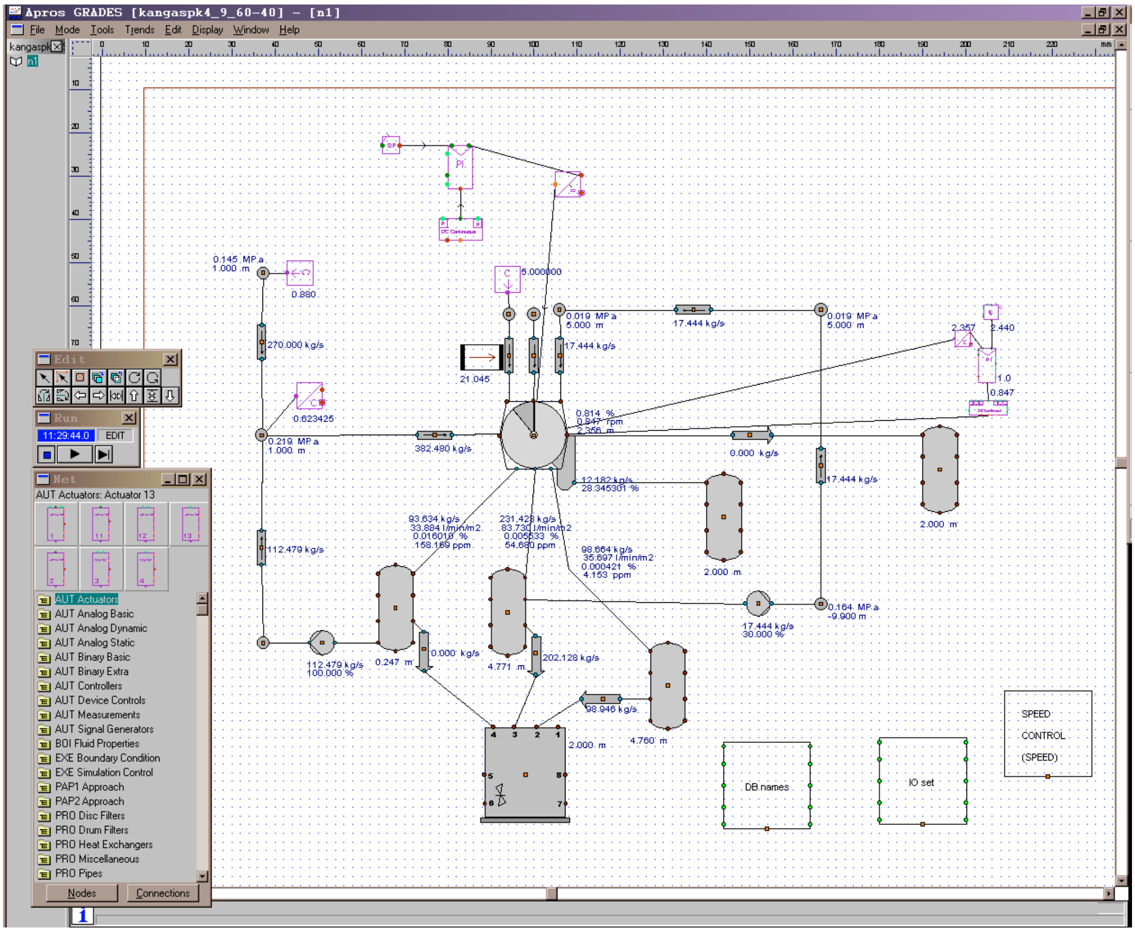

Figure 7 GRADES interface of a APROS/APMS simulator

The database of an APROS solver is built with different levels. The levels are shown in Figure 8.

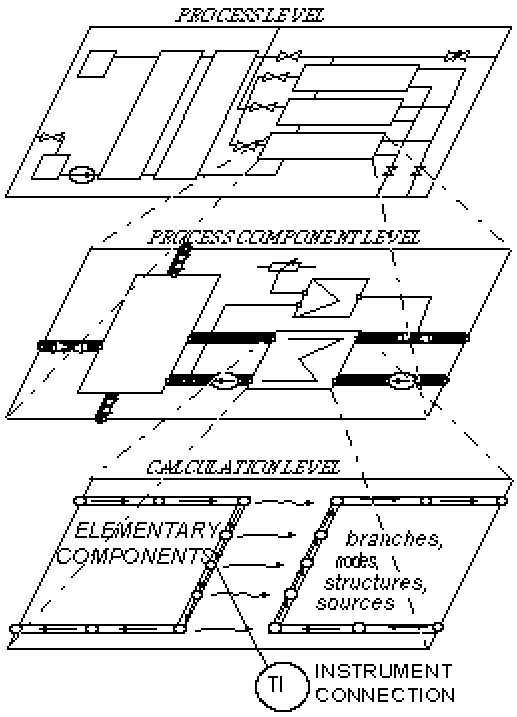

Figure 8 Hierarchical structure of an APROS solver.

Usually the simulator user works on the process component level. There is no need to see how the calculation level works, but it is possible to access that level also. If the user wants to add new models to the simulation (like a new process component), equations for the component are programmed to the calculation level.

4.4.1 External models in APROS

APROS provides mechanisms for users to include their own functional blocks in the simulation model and use them as a part of the APROS computation. This makes it possible for the user to specialise the process components currently implied in APROS or create a component of his own and make it a part of the simulation. The source codes of external models are not needed once the library has been built. This hides the model's functional details from the end-user.

The external model is written in C/C++ or FORTRAN and built into a shared, dynamically linkable library called DLL. In order to use the external model, it must be properly referred to in APROS. Every time the simulation comes to a point where the DLL is needed, it is called and executed by APROS. DLLs can be modified and recompiled between simulation runs without stopping and restarting APROS. This feature enhances the possibilities to test and develop external models in APROS.

There are four different types of external models in APROS. The external model of this work was an External 10-Reference Model. The name 10-Reference Model comes from the ten parameters for each data type. The data types are double, float, integer and logical (which are of integer type). All the parameters are direct addresses to the APROS memory area, which holds the information on the state of the process. All changes made to the parameters are also made to the memory area.

The APROS/APMS database is used in exchanging the data between various subroutines [17]. For maximal calculation speed the entire database is kept in the computer memory at all times. There is no separate database for external models. They also have direct access to the APROS/APMS database.

4.4.2 Module, Attribute and Variable

The simulated process is described by means of modules. A module represents a well-defined part or component in a physical process. The modules and their mutual connections are mapped onto a computational network and the process model can be simulated and modified without any program recompilations.

The modules consist of arrangements of calculation level elements. The governing differential equations of the process under study are solved using implicit methods. The properties of these elements and the solving method assures the independence from media flow and heat transfer directions when is necessary for the study of plant behaviour during simulation of severe plant equipment failures like pipe breaks etc. The data related to each physical process unit is grouped into the module corresponding to the unit.

Modules are typed; the module type defines the parameterisation and the behaviour of the module.

An attribute is a property of a module accessed through the owner module. Its value is fetched from the corresponding element in the variable table at request.

For maximal computation power, the data in the APROS database is organised in arrays accessed by solvers. The variables are also accessible by the user through the command prompt. Many of the variables correspond to module attributes, and there are also variables that do not correspond to any attribute.

5 Results of the Work

5.1 Type Definitions

The aim is to make Gallery such that any process component and related automation component can be described by its database definitions. Gallery Markup Language (GML) has been developed to enable this. GML is based on XML, which stands for *Extensible Markup Language*. GML is a meta model description for the data in the Gallery. If the user wants to put new pipeline components into the Gallery, he must first determine the *category* of the component. Under the category there is a *type definition* that describes all desired characteristics of the component.

5.1.1 Type Definitions of Filters

The categorisation of filters is based on the driving force of filtration. Filters can be vacuum operated or pressurised. Under each driving force there are *component types* for that category. Under vacuum filters for example there are vacuum disc filters, wires, vacuum belt filters etc. Type definitions contain parameters and values for the filters. The description can be as comprehensive as the manufacturer wants. The type definition should be such that the customers find all the necessary information they need from the device. It should also be such that simulation programs can be parameterised with Gallery data.

The filter department has three Filter Categories and a Filtration Measurement Data category. The Filter Categories are Vacuum Filters, Gravity Filters and Pressurised Filters. Under each filter category there are Component Types for the particular filter. Under Vacuum operated filters there are vacuum disc filters or vacuum belt filters. Figure 9 shows the hierarchy of the filters.

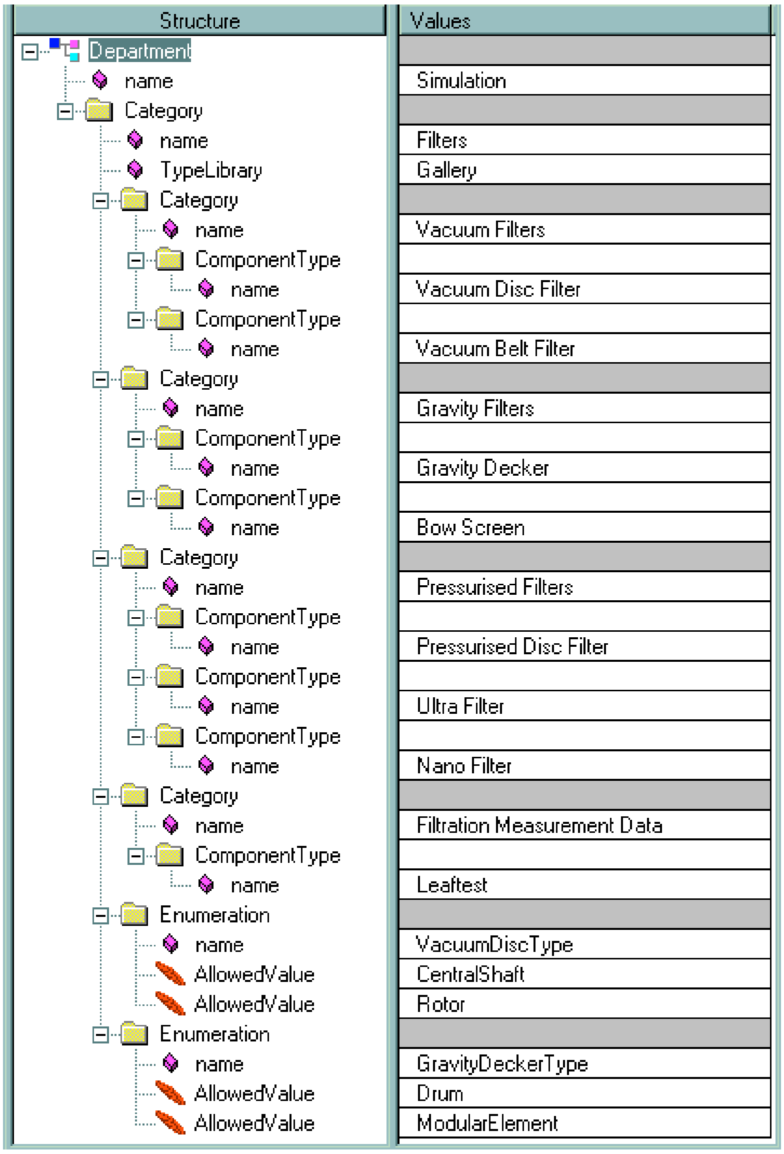

Figure 9 An example of filter categories in the Gallery.

Each filter can be described in as small detail as wanted. Vacuum disc filters have the following attributes:

- filter drawing
- knock off shower need per disc, m^3/s.
- number of discs, -
- space time, s
- motor, kW
- volume of a single disc, m^3
- volume of vat, m^3
- net mass, kg

- flooded mass, kg
- filter area, m^2
- diameter of disc, m
- length of vat, m
- vacuum disc type, central shaft or rotor
- number of sectors per disc, -
- service room need around the filter, m^2
- brochure, any product information brochure in digital form
- disc submerge percentage, %
- guaranteed values, a table of values the manufacturer guarantees for the product
  - wire water circulation, dm^3/min
  - maximum wire water consistency, mg/dm^3
  - maximum wire water ash content, %
  - min-max wire water pH, -
  - min-max wire water temperature, °C
  - sweetener type, for example LWC, TMP etc.
  - sweetener freeness, ml CSF
  - etc...
- flow charts, a drawing
- other remarks, a text file

5.1.2 Type Definition of Leaftest Data

The objective of this thesis was to study the use of measurement data in process component simulation. In order to create a filter-specific simulation model, measurements of an individual filter or a more general model built from several measurements must be utilised. Filter test data was received in a leaftest form, which was (like the filters) written with GML. Gallery user can download measurements of filters as well as filter characteristics and also simulate individual filters.

The rotary disc filter manufacturer GL&V has a measurement data database that they use for dimensioning the filters according to customer's needs. The measurements are called leaftests. Each leaftest is a table of process conditions and results for a particular filter. Importing leaftests into Gallery enables GL&V customers to study how their filters would behave, if they for example changed the type of production. It is entirely up to GL&V to determine how much information they want to put into Gallery and more importantly how extensively they want to show it to their customers. The measurements are numbered. Every measurement has the following information fields:

- rotational speed, 1/min
- static pressure
- vacuum, m water
- sweetener
  - type, for example LWC, TMP, etc.
  - consistency, %
  - freeness, ml CSF
  - flow, kg/min
  - white water
  - consistency, %
  - ash content, %
  - flow, kg/min
- angle of offset, °
- inlet mix consistency, %
- S-R
- temperature, °C
- filter cake
  - area, cm^2
  - weight wet, g
  - weight dry, g
  - thickness, mm
- consistency, %
- BDMTPD/m^2
- amounts of cloudy, clear and super clear filtrate (sample), ml
- consistencies of cloudy, clear and super clear filtrate (sample), ml
- total drainage, $dm^3/min/m^2$
- ADMTPD/m^2
- information on the factory, process conditions, application, type of production etc.

5.2 Dynamic Link Library

A dynamic-link library (DLL) contains one or more subprogram procedures (functions or subroutines) that are compiled, linked, and stored separately from the applications that use them. Because the functions or subroutines are separate from the applications using them, they can be shared or replaced rather easily. The disc filter external model can be used in the simulation program as well as in the Gallery server. There is no need to modify and compile the main program (or any other programs that uses the DLL) each time something changes.

DLL is an executable file. Unlike the static library, where routines are included in the base executable image during linking, the routines in DLL are loaded when an application that references that DLL is loaded. This happens during the run time. A DLL can also be used as a place to share data across processes.

5.3 External model (Black Box)

External models in APROS are “black boxes”, because they are software components that hide their implementations from the user. They can transfer information from the Gallery to the simulation programs. The black box can be for example a correlation for process component variables under different process conditions.

In this work a black box was used for a rotary disc filter. It makes more accurate simulation possible for the user, who has access to Gallery containing disc filter measurement data.

The external model has been implemented with C++ programming language. The model is a dynamic link time library (DLL) of Microsoft Windows.

5.3.1 Input/output of the External Model

There are many different things that affect the function of a rotary disc filter. In this work a model was built that takes into account four variables: rotational speed of the disc (revolutions per minute), inlet concentration (concentration in the vat was assumed equal to the feed), freeness (ml CSF, determines the type of production) and angle of offset (degrees). Angle of offset is a manufacturer-specific parameter, which is used to determine the ratio between the amounts of cloudy and clear filtrates.

The model is largely based on measurement data of Celleco Hedemora VDF, which is a classic central shaft disc filter. There is no mechanism that would simulate other disc filter types, but filtration results depend less on the filter type and more on the mass type that is being filtrated.

Non-linear regression analysis was made to define parameters in the model using few good measurements made with half a dozen different masses that had freenesses between 90 ml and 550 ml.

Input of the external model is:

- rotational speed
- freeness
- input consistency
- angle of offset

Output of the external model is:

- filtrate fluxes (calculated as percentages of the total drainage)
  - cloudy filtrate
  - clear filtrate
  - super clear filtrate
- consistencies of each filtrate

5.3.2 Finding Shape for the Model

The model is based on measurement records for five masses that had different freenesses. Two of the records were complete. They contained rotational speed, inlet consistency, sweetener freeness and angle of offset. The total drainage, drainage of each filtrate and their consistency were measured by altering all four parameters. Both of the measurement records were made with masses that had slightly over 500 ml CSF freeness.

The additional three measurement records contained only total drainage and clear filtrate drainage together with clear filtrate consistency. The drainages and consistencies were plotted against rotational speed. The masses had freenesses below and above 100 ml CSF.

The model needs to calculate also consistencies and drainages of cloudy and super clear filtrates. Those measurements were missing from the incomplete records so they were constructed by examining the complete measurement records. Angle of offset was also missing from the records. It was assumed to be 60°, which is a common value for it.

With two complete and three manually completed measurement records a search for a general disc filter model started. The measurements were put into a spreadsheet program and a regression analysis was made. The aim was to surpass the accuracy of the original model [1]

$$y = k_1\omega + k_2 c_{\mathrm{vat}}$$

where c_{vat} consistency in the vat

The first function was simply a linear presentation that contained four variables. The constructed drainages and consistencies were then manipulated to yield a model that gave the best fit to the measurements. A linear fit was tried first. Since the original model was also linear and used only two parameters it was natural to make the model more comprehensive by adding the essential sweetener freeness and also an angle of offset. The model was

$$q = k_1\omega + k_2 c_{\mathrm{inlet}} + k_3 fr + k_4\theta + k_5$$

where ω rotational speed of the filter

c_{inlet} inlet concentration of the feed

fr freeness of the sweetener

θ angle of offset

There were individual coefficients for

- total drainage
- cloudy, clear and super clear drainages as percentages of the total drainage
- cloudy, clear and super clear filtrate consistencies

Each of the above had individual coefficients. The number of coefficients was five times seven which makes 35.

The results were acceptable although with very low freeness numbers, the drainages were too low. The original version used a linear model, so it was necessary to find a form that was more consistent with the measurements. Disc filter filtration curves are such that from zero to 1 rpm drainages and consistencies generally rise faster than above 1 rpm. It was possible to find a form that would represent that behaviour better than a linear model.

Several different forms of the equations were tried. Combinations of terms, one term divided by another term, exponents for each term etc. There was an endless number of possible forms for each of the seven equations, which yielded an endless amount of more or less optimal solutions to the problem. Finally a sum of different terms that each had their own exponent was chosen. The equation is

$$q = k_1 \left(\frac{\omega}{\frac{1}{\min}} \right)^a + k_2 \left(\frac{c_{\text{inlet}}}{\%} \right)^b + k_3 \left(\frac{fr}{\text{ml}} \right)^c + k_4 \left(\frac{\theta}{\deg} \right)^d + k_5 \qquad (21)$$

where a, b, c, d exponents

The total number of coefficients is 63. After finding a good general fit many of the parameters were manually tuned. The equations were given to the manufacturer and according to their feedback the model was modified so to suit the measurements better. This procedure was repeated several times over. Since the model is a general presentation, the manufacturer could compare the results with the measurements they considered most important. Table II shows the coefficients $k_1 - k_5$ and exponents *a*-*d* for flows and consistencies.

Table II Coefficients and exponents of a disc filter external model. The model is $q_{\mathrm{tot}} = k_1\omega^a + k_2 c_{\mathrm{inlet}}^b + k_3 fr^c + k_4\theta^d + k_5$. It gives total drainage, percentages of different filtrate drainages and their consistencies. Boundary conditions for the input values are listed in Table III.

	k_1	k_2	k_3	k_4	k_5	*a*	*b*	*c*	*d*
total drainage of the filter	185.00	40.00	0.198	-1.030	-140.0	0.30	-1.0	1.000	1.000
cloudy filtrate drainage percentage	-0.0262	-0.0119	-0.436	-9.007	8.40	2.00	-2.0	-0.046	-0.038
clear filtrate drainage percentage	0.0179	0.0926	1.807	11.216	-10.71	2.00	-2.0	-0.046	-0.038
super clear filtrate drainage percentage	0.0010	-0.0235	-0.755	-1.162	1.84	2.00	-2.0	-0.046	-0.038
cloudy filtrate consistency	498.59	181.86	-0.352	-0.7160	-239.5	0.30	1.0	1.000	1.000
clear filtrate consistency	180.33	147.10	-0.155	0.0004	-170.0	0.30	1.0	1.000	1.000
super clear filtrate consistency	88.98	63.82	-0.071	0.0058	-83.0	0.30	1.0	1.000	1.000

Since the model is based purely on measurement data that consists only of a measurement made under normal process conditions, it may give unrealistic results if the variables exceed certain limits. Boundaries had to be set for the variables. They are presented in Table III.

Table III Boundary input values for the external model. Outside these limits the simulation results may be unreliable.

	rotational speed, 1/min	inlet consistency, %	freeness, ml	angle of offset, °
min value	0.5	0.7	30	40
max value	1.5	0.9	600	60

If the calculation exceeds any of the limits in Table III, the program does not stop the calculation, but it displays a warning that states that the results may be unreliable.

The model might give under certain conditions output values for drainages and consistencies slightly below zero around 0.5 rpm. Otherwise the model is stable though it looks rather complex.

Figures 10-16 show how much and how clean filtrate can be expected to be for different types of paper production when the filter rotates 0.5-1.0 rpm. The curves are drawn by using the equations for the external model. They are calculated for constant inlet consistency (0.8 %) and constant angle of offset (60°). The APMS simulator results can be found in Figures 18-39.

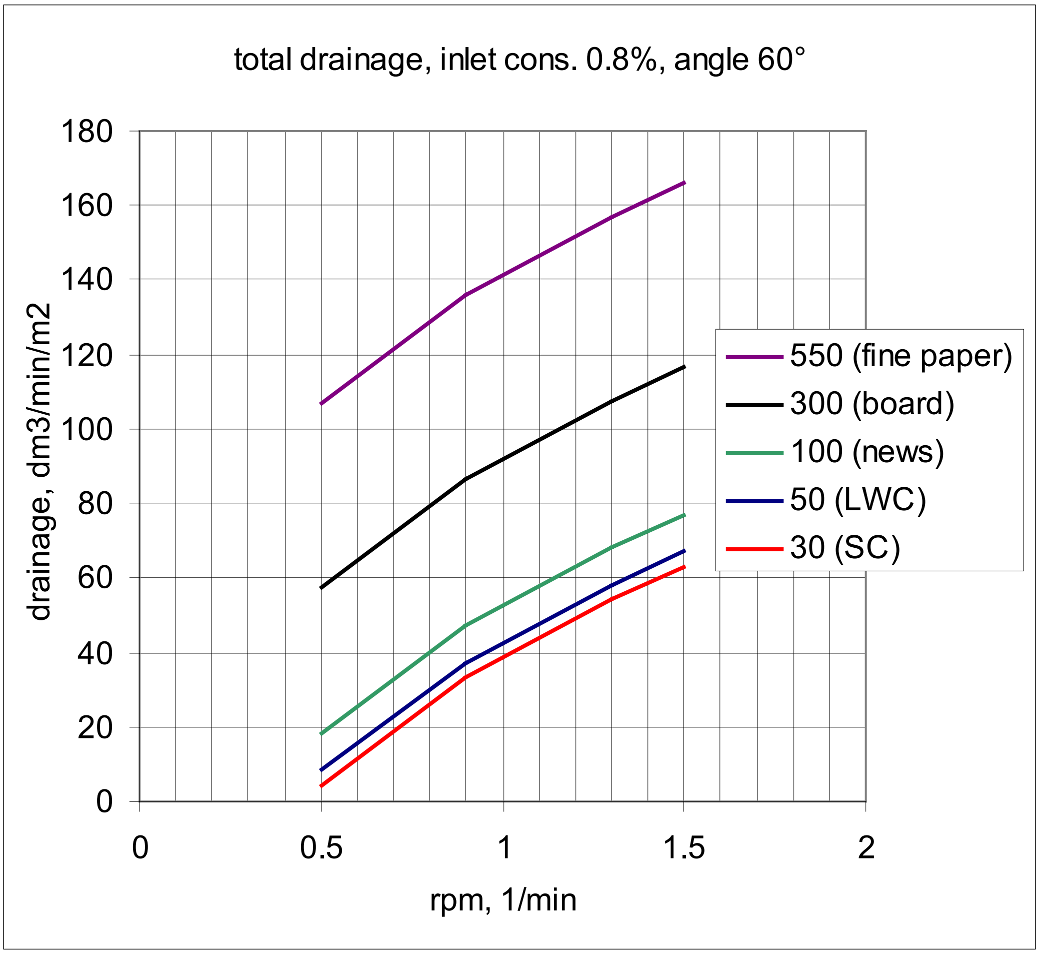

Figure 10. Total drainage of different types of paper production calculated by the disc filter external model. The number in front of the paper type implies typical sweetener freeness.

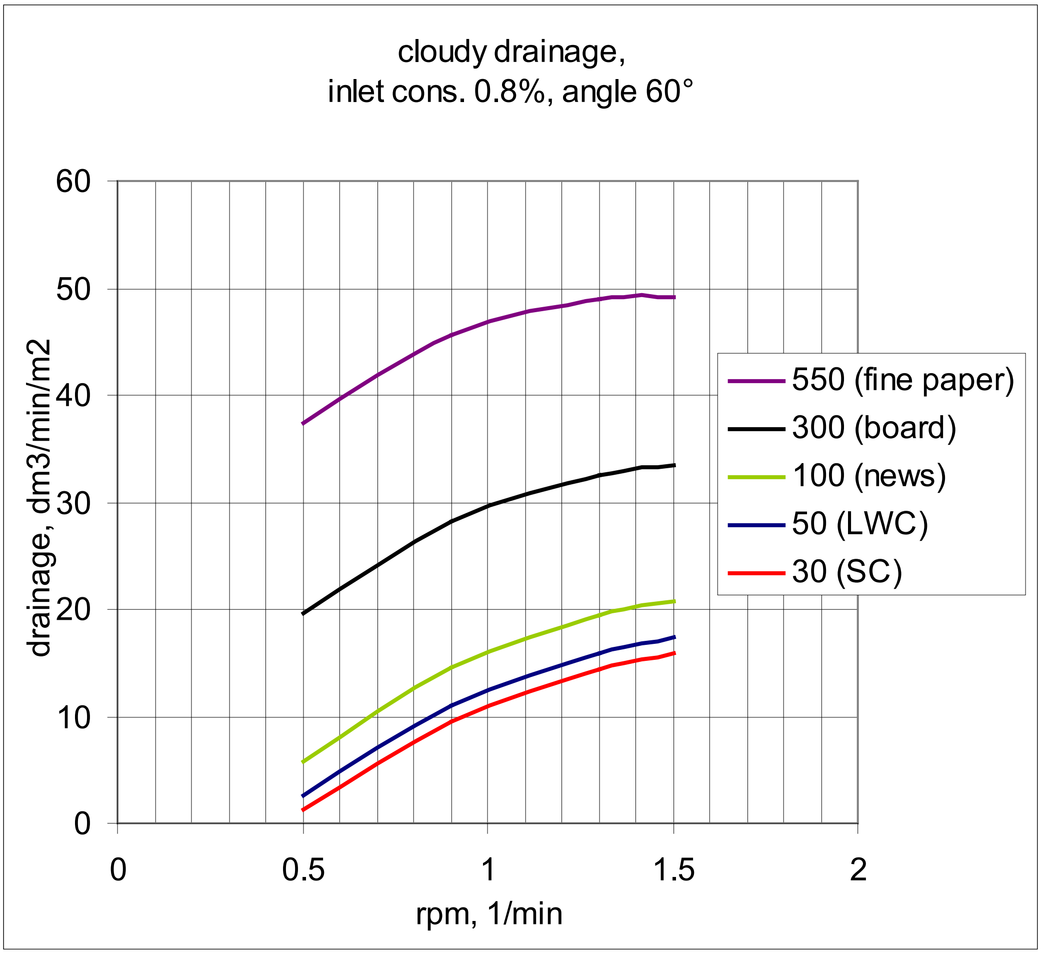

Figure 11. Cloudy filtrate drainages for different types of paper production calculated by the disc filter external model. The number in front of the paper type implies typical sweetener freeness.

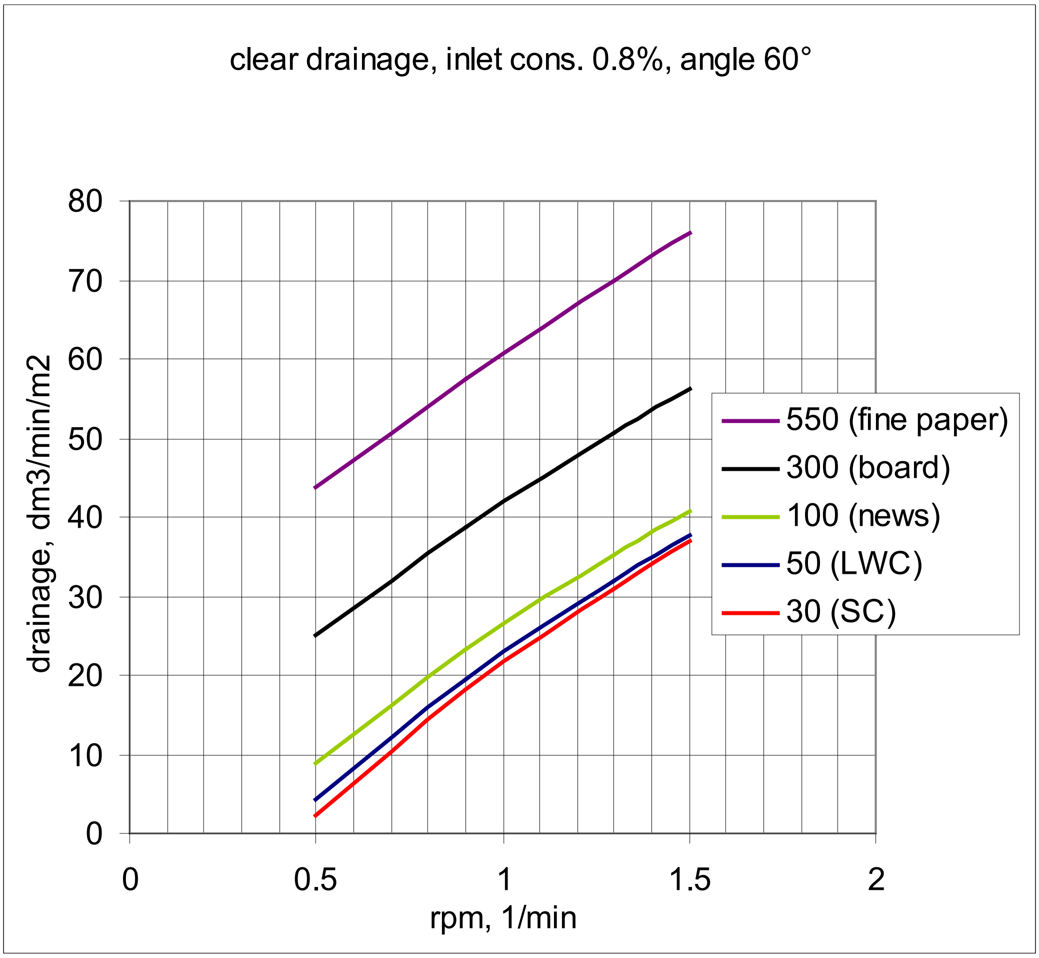

Figure 12. Clear filtrate drainages for different types of paper production calculated by the disc filter external model. The number in front of the paper type implies typical sweetener freeness.

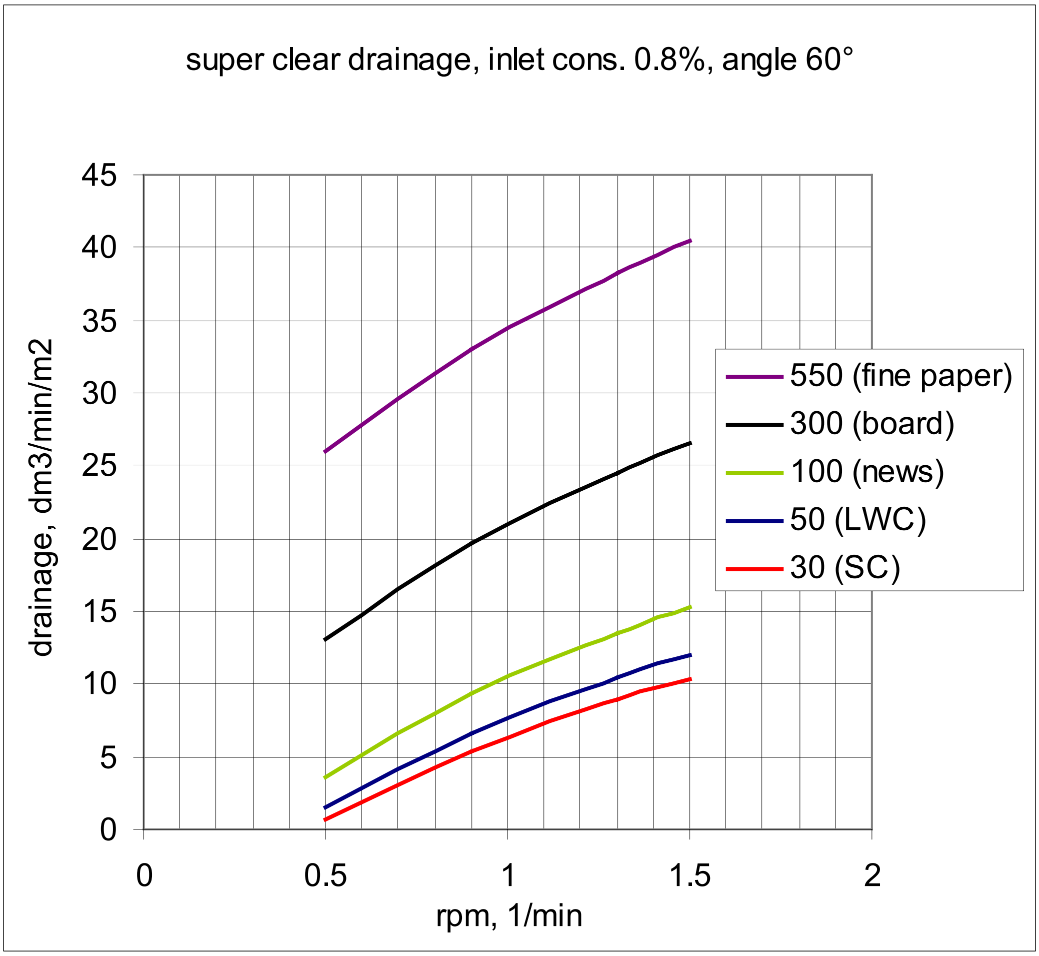

Figure 13. Super clear filtrate drainages for different types of paper production calculated by the disc filter external model. The number in front of the paper type implies typical sweetener freeness.

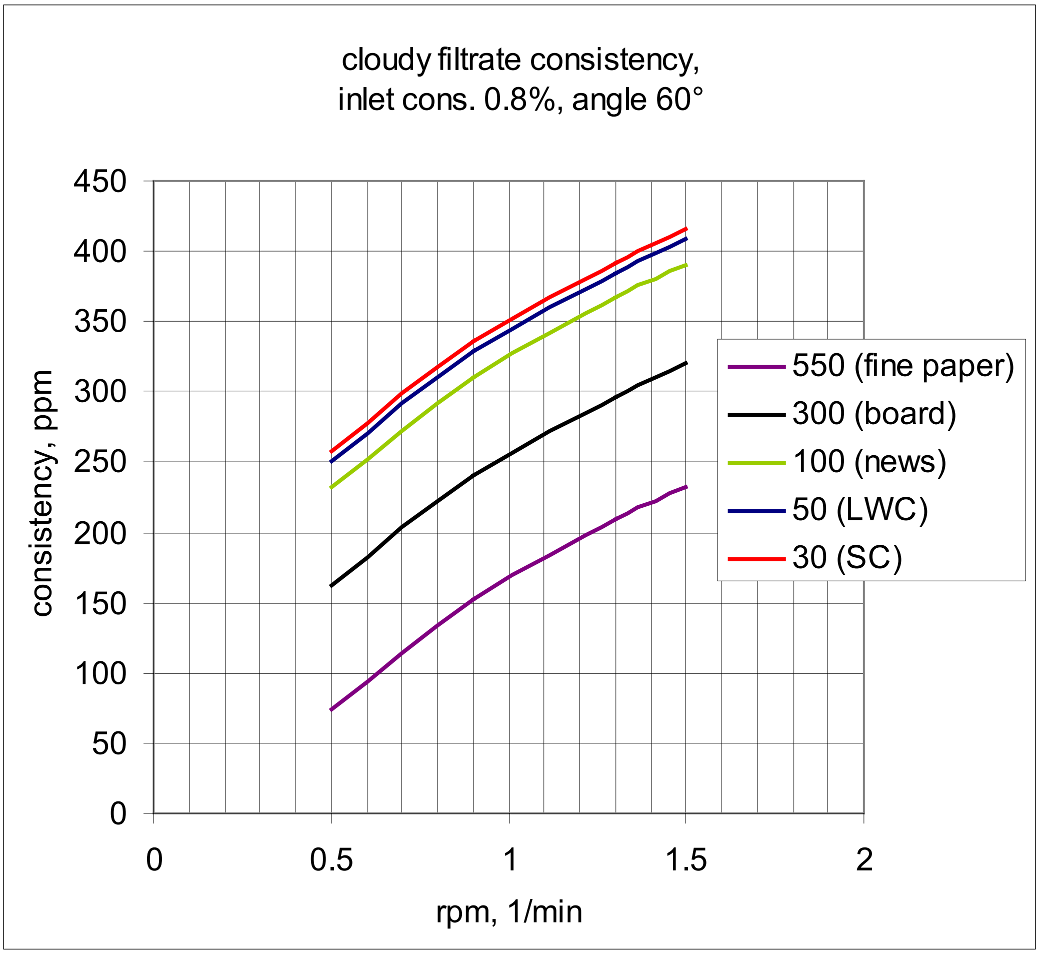

Figure 14. Consistency of cloudy filtrates for different types of paper production calculated by the disc filter external model. The number in front of the paper type implies typical sweetener freeness.

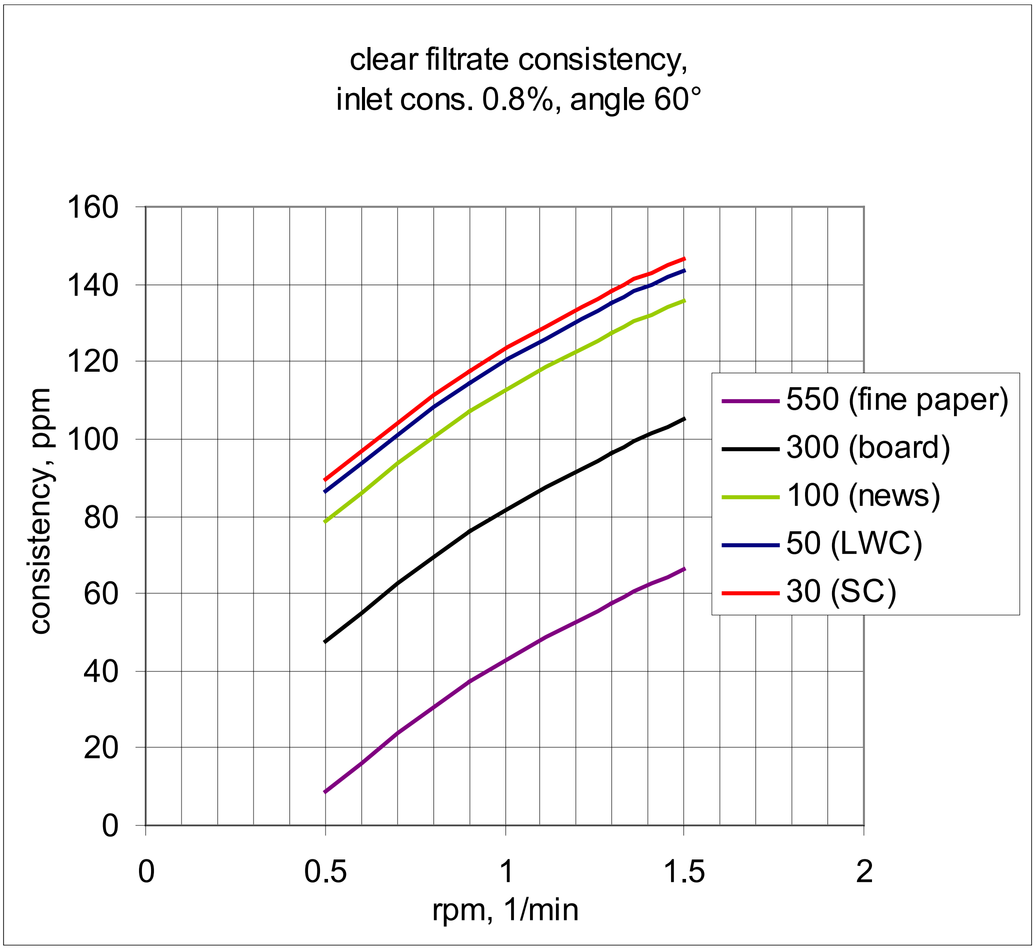

Figure 15. Consistency of clear filtrates for different types of paper production calculated by the disc filter external model. The number in front of the paper type implies typical sweetener freeness.

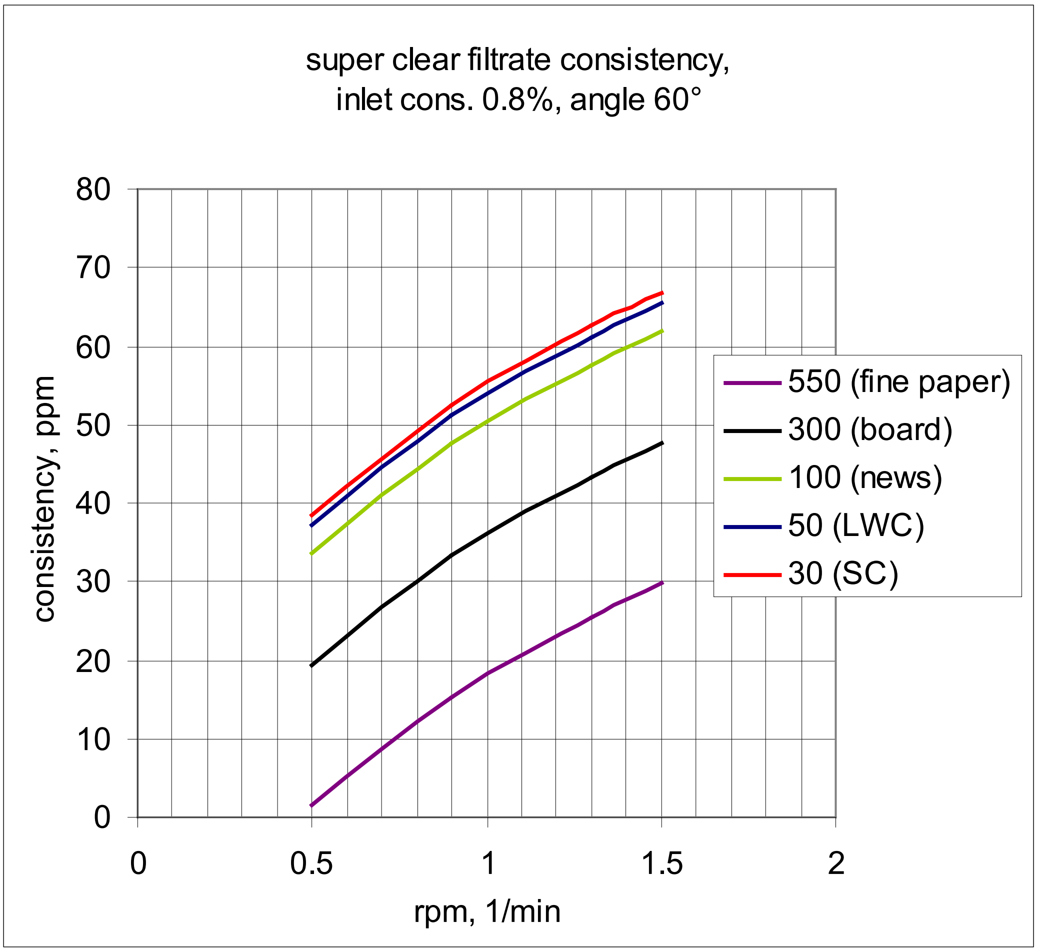

Figure 16. Consistency of super clear filtrates for different types of paper production calculated by the disc filter external model. The number in front of the paper type implies typical sweetener freeness.

5.3.3 Restrictions of the Model

The length of each drop leg is equal and there is no mechanism that enables the user to simulate different drop legs for each filtrate. There are no different mass types and the mass is “selected” by giving a typical freeness to the desired mass.

5.3.4 Another Approach

The original intention was to make an external model that would use individual measurement data for each filtration case. The user would determine sweetener type, production type, device, temperature, pH and even perhaps a specific factory or a country, which all have an effect on the filtration characteristics. The model would have searched its measurement database and selected the best possible measurement available for the situation. If you make news print and want to know how the filter would behave if you suddenly change the production into deink or board, the external model would have found the right measurement record from the database. Then it would have calculated coefficients for a model that has one or more variables. It would have given the process engineer a tool for extremely accurate simulation models.

This kind of model was unfortunately not possible to create since the essential information flow between VTT and the filter manufacturer was hindered for a prolonged time during the work. The model could have been tested with one or two masses that had almost the same freeness, but it would have left little or no room to compare the results with anything outside the very same measurements on which the model itself was based on. This would obviously have resulted in negligible benefit from the work, especially since the manufacturer wished for a more general presentation of filtration. Measurements could have been created to test the mechanism but it would have been impossible to test the accuracy of the model with real results.

The original approach was implemented almost to the full, but unfortunately it had to be discarded from the final version in this work. Co-operation with the manufacturer continues and since the original approach is still very much possible the final version of the Gallery is likely to include both the original approach and the external model implemented in this work.

5.4 Testing the Model in APMS

The external model was tested against the manufacturer's own measurements and the original disc filter model. Figure 17 shows the test environment built in APMS. The filter is in the middle. White water and sweetener are mixed in the input and most of cloudy filtrate is circulated back into the filter. There is a level meter in the vat. The liquid level is controlled by changing the rotational speed of the filter so that the level stays constant. Super clear filtrate is removed from the process and part of clear filtrate is used in filter showers. Pulp is removed from the process.

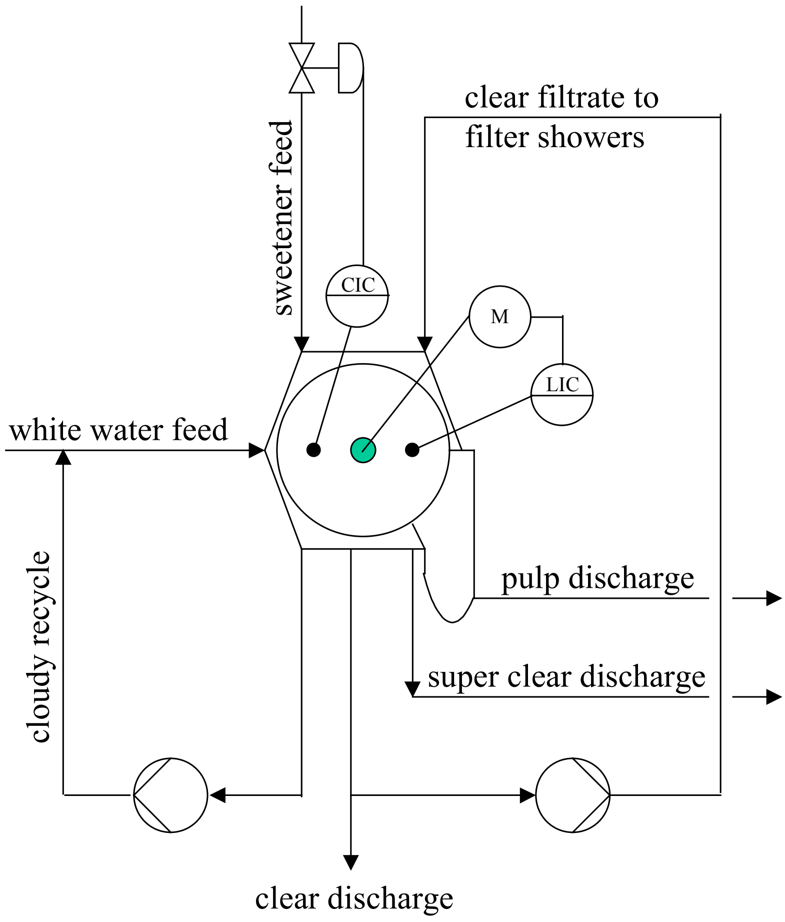

Figure 17 Flow chart of the test process in APMS.

5.4.1 Step Change Diagrams

Figures 18-28 show the results from the step change responses of the external model. Step changes were made for rotational speed, inlet consistency, freeness and angle of offset. The disc submerge percentage was set to 65% with a liquid level controller. GL&V is actually able to submerge up to 70% of their discs, but 65% is a safe assumption for normal operational conditions.

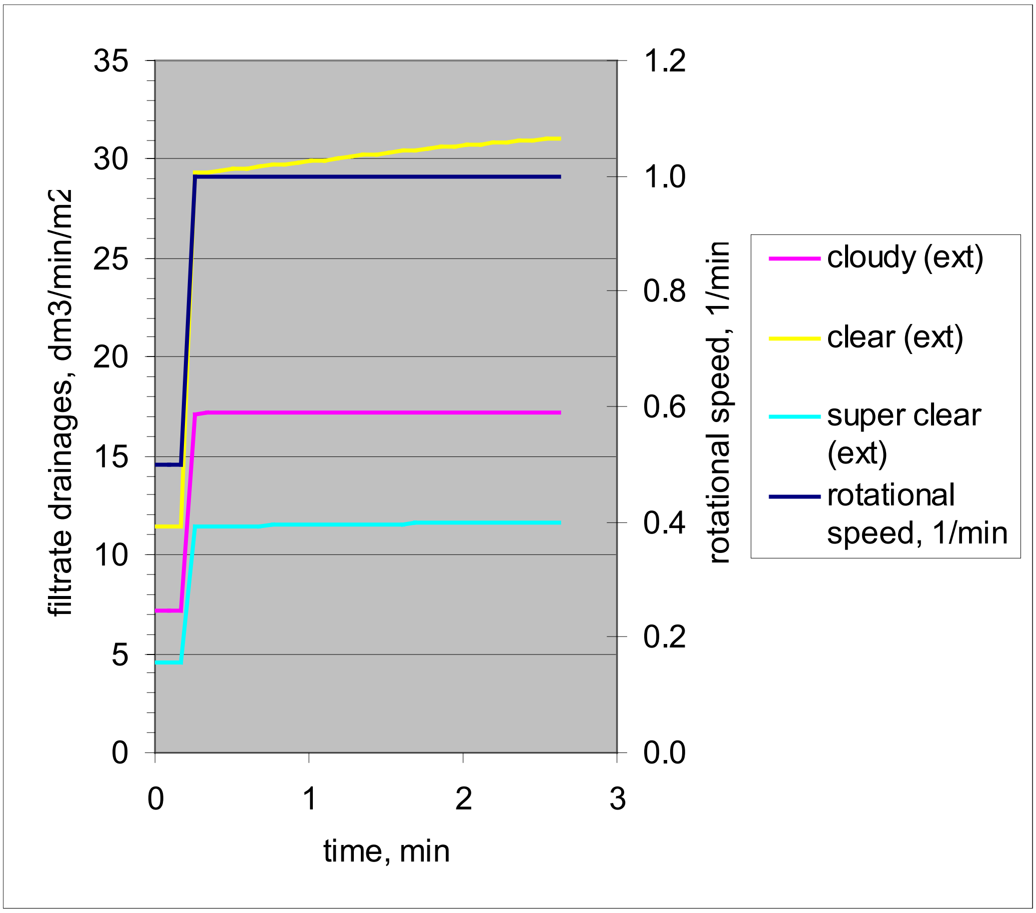

Figure 18 Step change in the rotational speed and step response for the drainages of filtrates calculated by the disc filter external model. Feed consistency 1.0 %, freeness 100 ml, angle of offset 60°, disc submerge 65%. Inlet consistency was around 0.8 %. Cloudy filtrate was recycled back into the filter. Results were simulated with APMS. The simulated filter had 12 discs and a total area of 168 m^2.

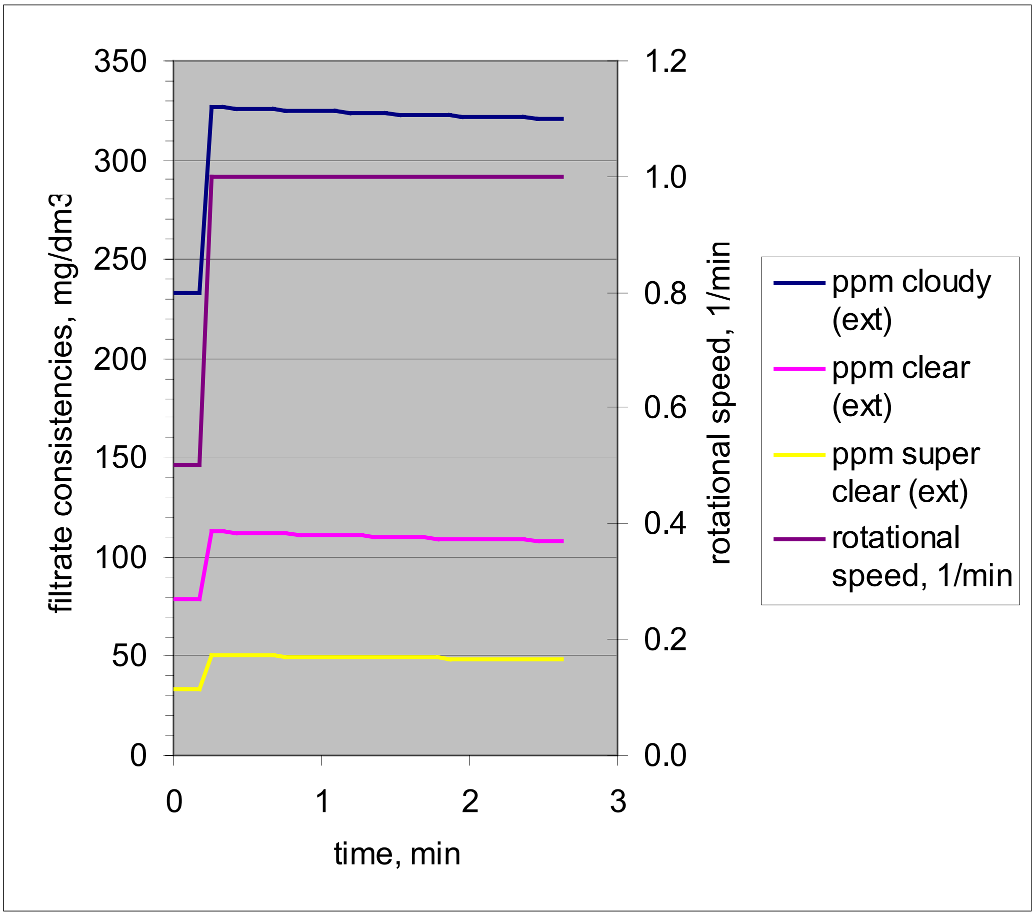

Figure 19 Step change in the rotational speed and step response of the consistencies of filtrates calculated by the disc filter external model. Feed consistency 1.0 %, freeness 100 ml, angle of offset 60°, disc submerge 65%. Inlet consistency was around 0.8 %. Cloudy filtrate was recycled back into the filter. Results were simulated with APMS. The simulated filter had 12 discs and a total area of 168 m^2.

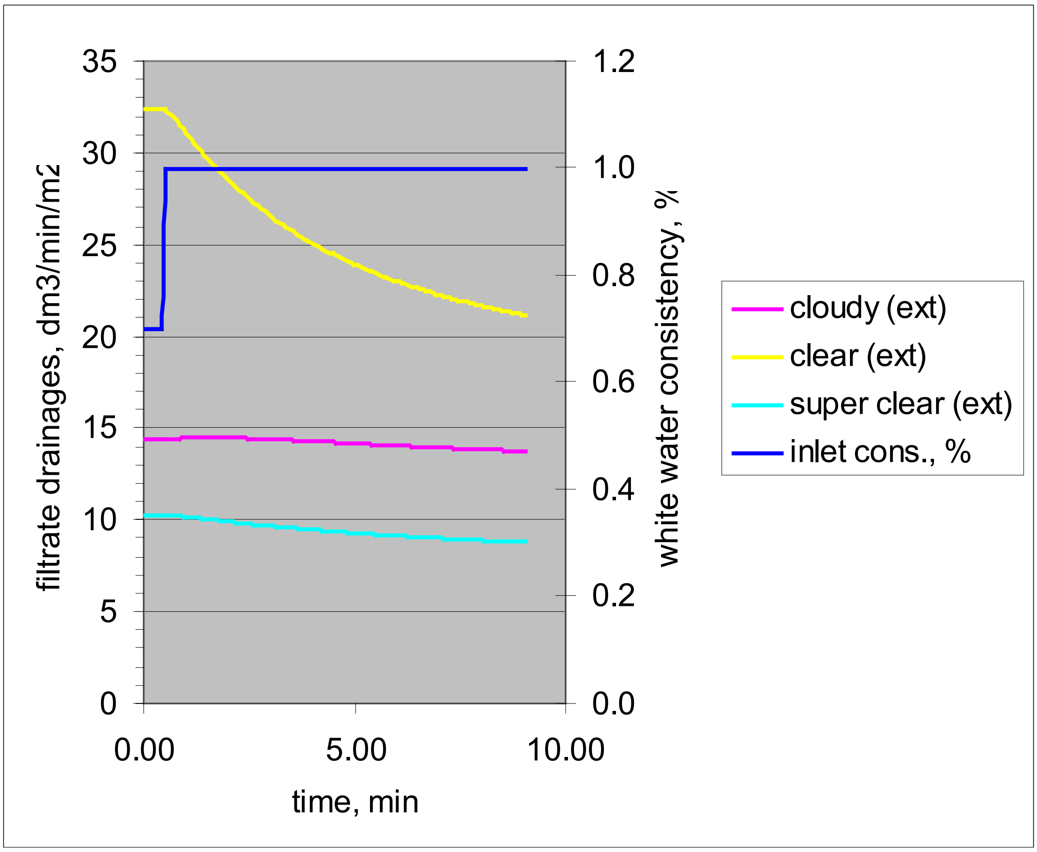

Figure 20 Step change in the inlet consistency and step response of the drainages of filtrates calculated by the disc filter external model. Feed consistency changed from 0.7 to 1.0 %, freeness 100 ml, angle of offset 60°, disc submerge 65%. The rotational speed was fixed at 0.81 rpm. Cloudy filtrate was not recycled back to the filter. Results were simulated with APMS. The simulated filter had 12 discs and a total area of 168 m^2.

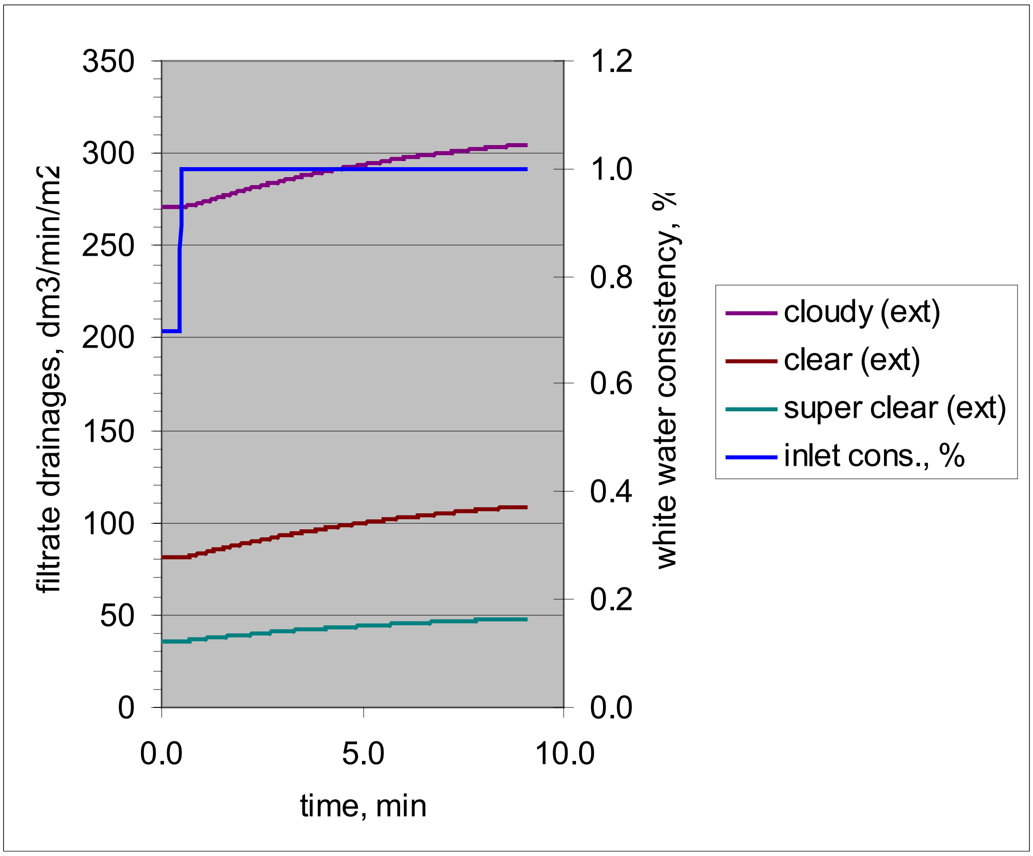

Figure 21 Step change in the inlet consistency and step response of the consistencies of filtrates calculated by the disc filter external model. Feed consistency changed from 0.7 to 1.0 %, freeness 100 ml, angle of offset 60°, disc submerge 65%. The rotational speed was fixed at 0.81 rpm. Cloudy filtrate was not recycled back into the filter. Results were simulated with APMS. The simulated filter had 12 discs and a total area of 168 m^2.

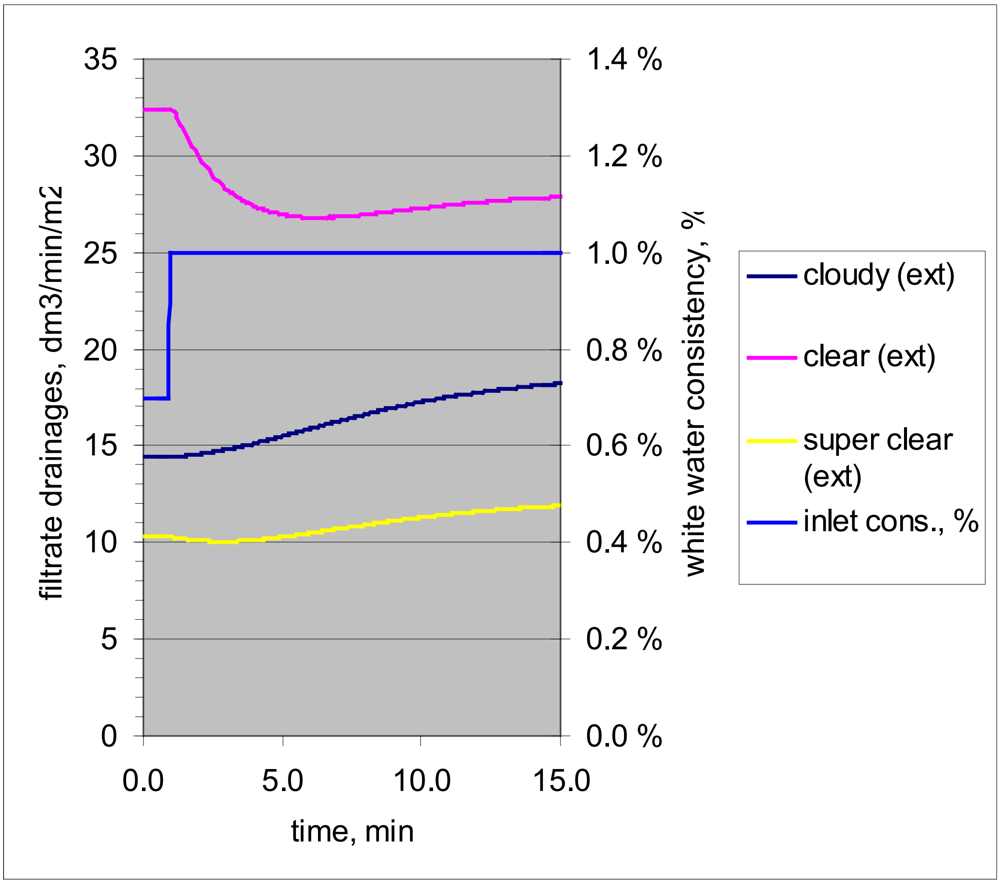

Figure 22 Step change in the inlet consistency and step response of the drainages of filtrates calculated by disc filter external model. The feed consistency changed from 0.7 to 1.0 %, freeness 100 ml, angle of offset 60°, disc submerge 65%. The rotational speed was controlled with a rotational speed controller. Cloudy filtrate was recycled back to the filter. Results were simulated with APMS. The simulated filter had 12 discs and a total area of 168 m^2.

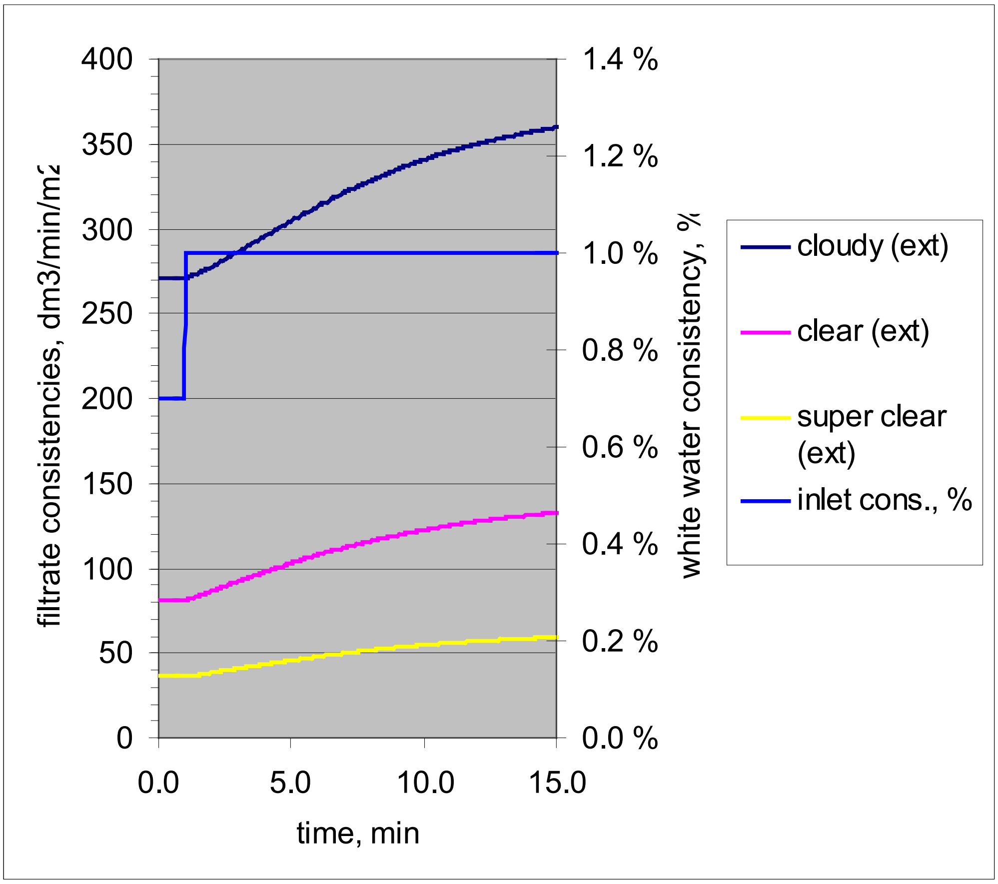

Figure 23 Step change in the inlet consistency and the step response of the consistencies of filtrates calculated by the disc filter external model. The feed consistency changed from 0.7 to 1.0 %, freeness 100 ml, angle of offset 60°, disc submerge 65%. The rotational speed was controlled with a rotational speed controller. Cloudy filtrate was recycled back into the filter. Results were simulated with APMS. The simulated filter had 12 discs and a total area of 168 m^2.

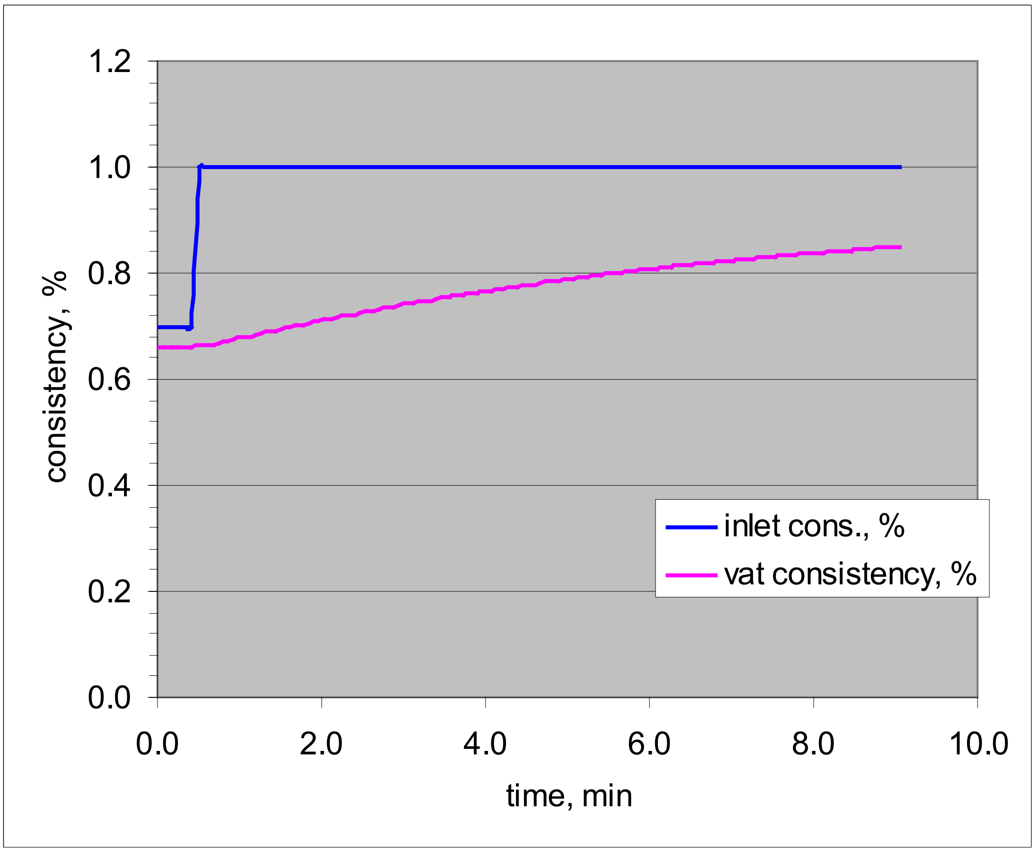

Figure 24 Step change in the inlet consistency and step response of vat consistency. Feed consistency changed from 0.7 to 1.0 %, freeness 100 ml, angle of offset 60°, disc submerge 65%. The rotational speed was fixed at 0.81 rpm. Cloudy filtrate was not recycled back to the filter. Results were simulated with APMS. The simulated filter had 12 discs and a total area of 168 m^2.

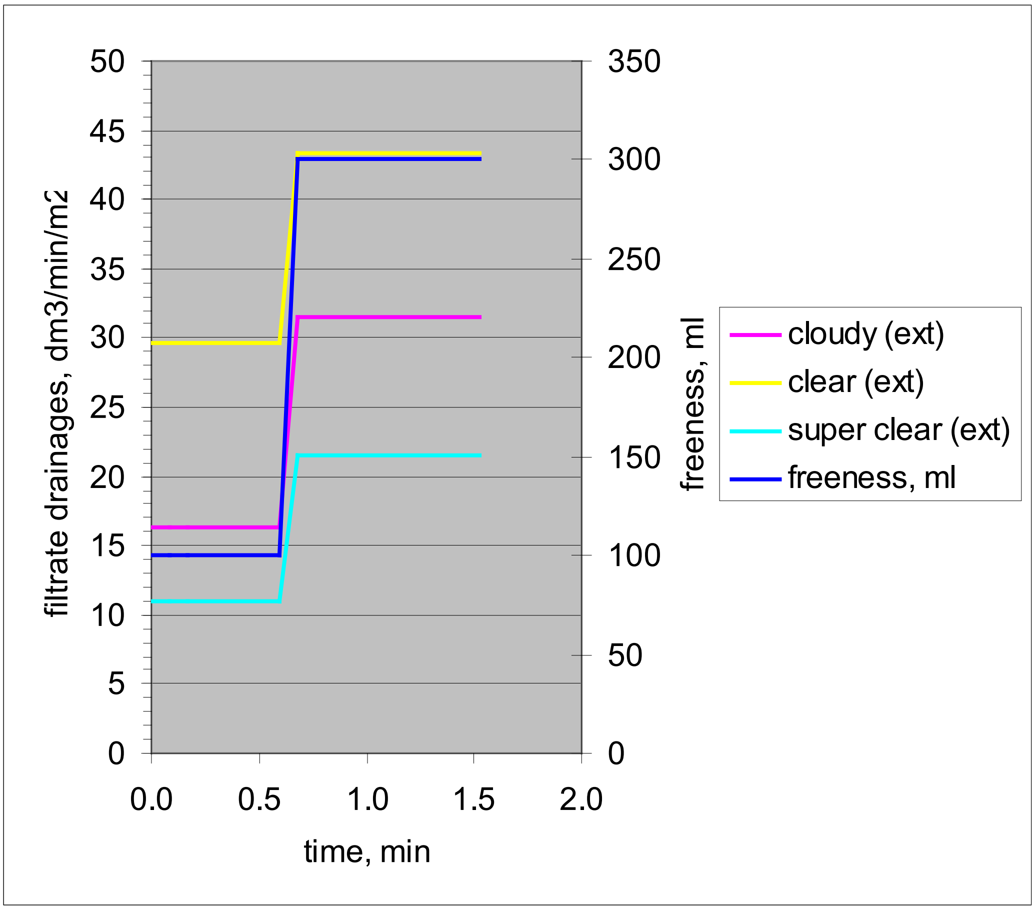

Figure 25 Step change in the freeness and step response of the drainages of filtrates calculated by disc filter external model. Freeness changed from 100 ml to 300 ml, angle of offset 60°, disc submerge 65%. The rotational speed was fixed at 0.93 rpm. The cloudy filtrate was recycled back to the filter. Results were simulated with APMS. The simulated filter had 12 discs and a total area of 168 m^2.

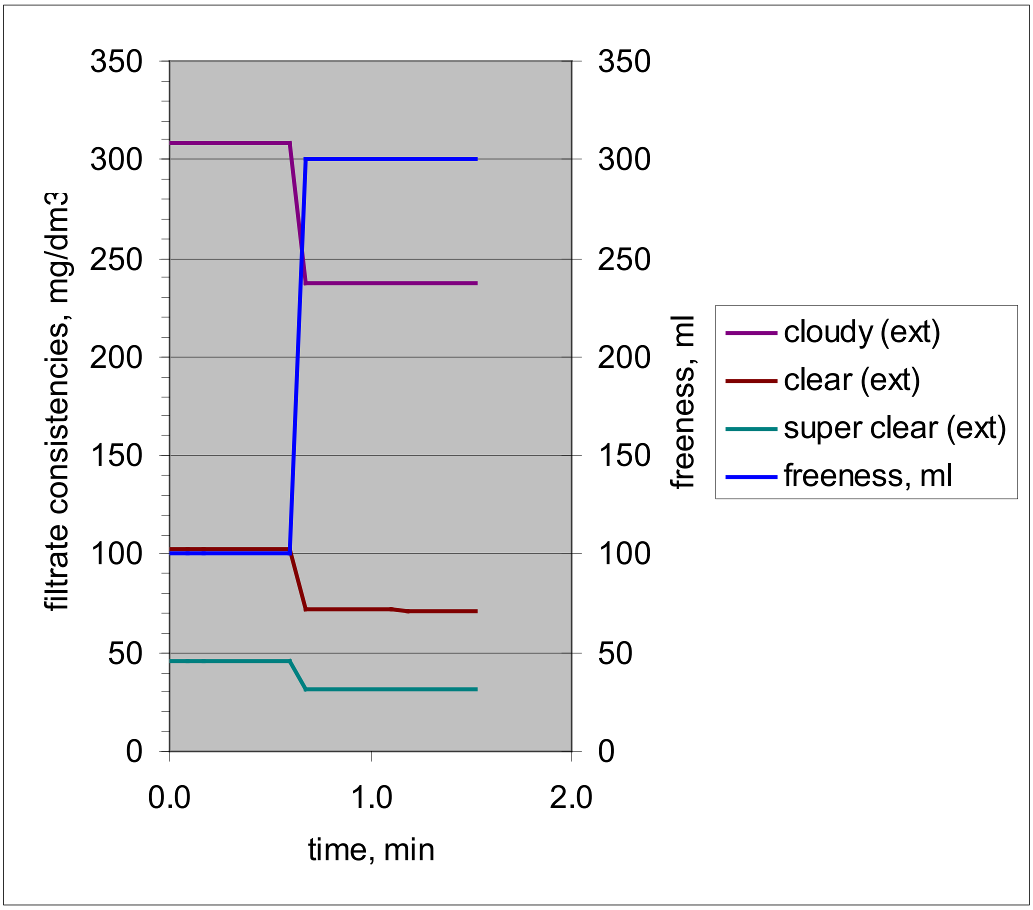

Figure 26 Step change in the freeness and step response of the consistencies of filtrates calculated by disc filter external model. Freeness changed from 100 ml to 300 ml, angle of offset 60°, disc submerge 65%. The rotational speed was fixed at 0.93 rpm. The cloudy filtrate was recycled back to the filter. Results were simulated with APMS. The simulated filter had 12 discs and a total area of 168 m^2.

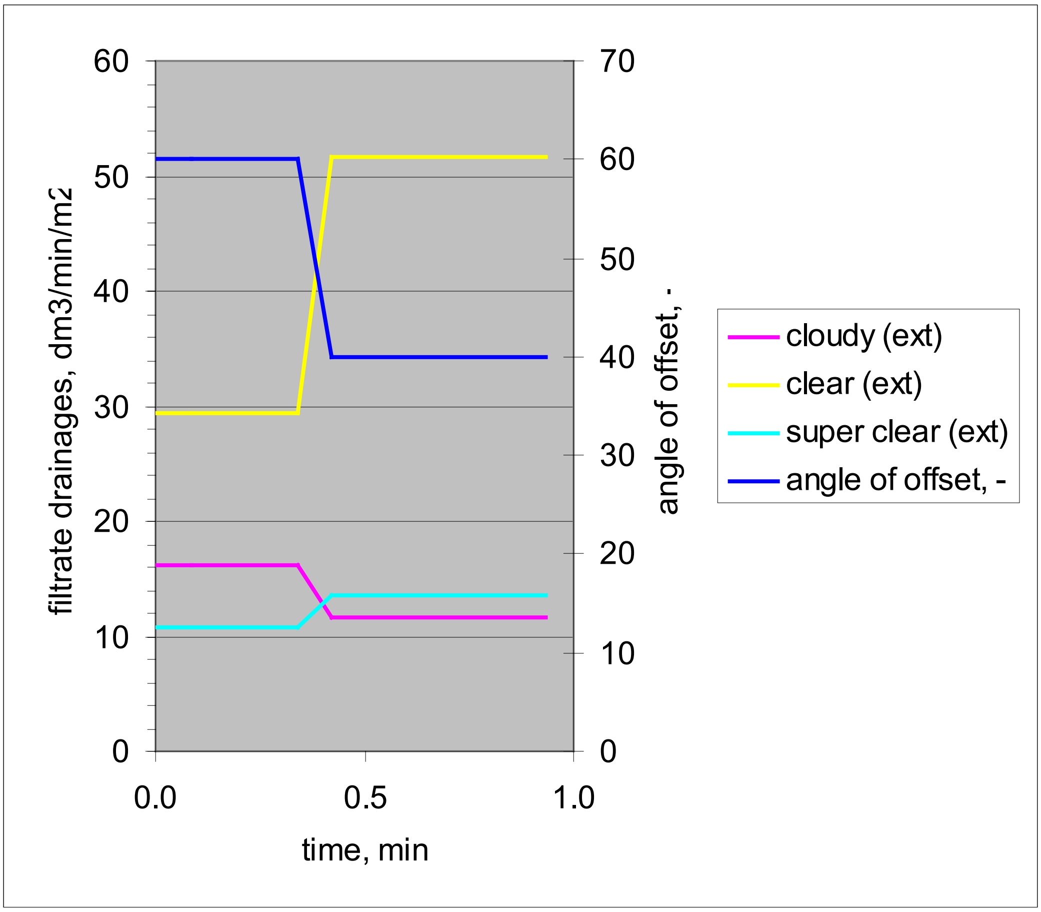

Figure 27 Step change in the angle of offset and step response of the drainages of filtrates calculated by the disc filter external model. The angle of offset changed from 60° to 40°, disc submerge 65%. The rotational speed was fixed at 0.92 rpm. Cloudy filtrate was recycled back to the filter. Results were simulated with APMS. The simulated filter had 12 discs and a total area of 168 m^2.

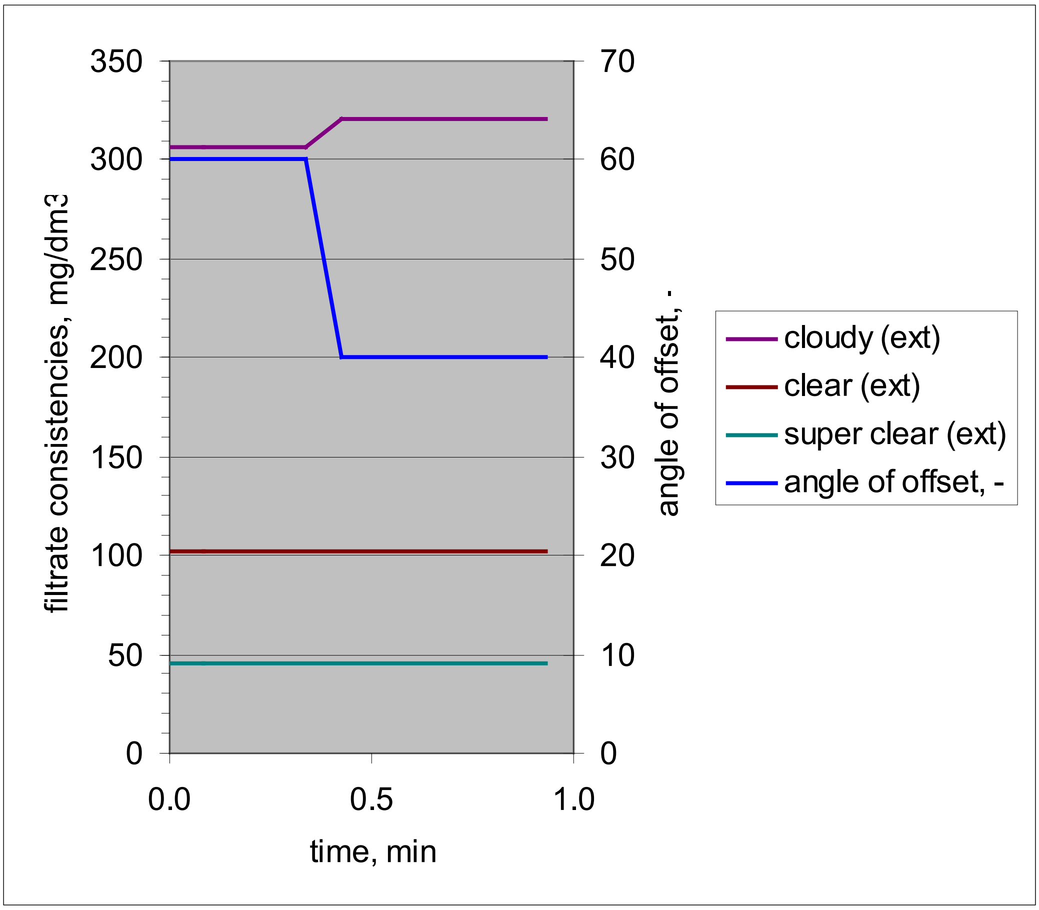

Figure 28 Step change in the angle of offset and step response of the consistencies of filtrates calculated by the disc filter external model. The angle of offset changed from 60° to 40°, disc submerge 65%. The rotational speed was fixed at 0.92 rpm. Cloudy filtrate was recycled back to the filter. The results were simulated with APMS. The simulated filter had 12 discs and a total area of 168 m^2.

5.4.2 Responses for an Operational Control System

The following figures are drawn for a fully operational control system. Vat consistency was controlled with consistency control that kept the vat at 0.8 % consistency. Rotational speed was controlled by the speed controller that kept the vat level matching 65 % submerge of the disc.

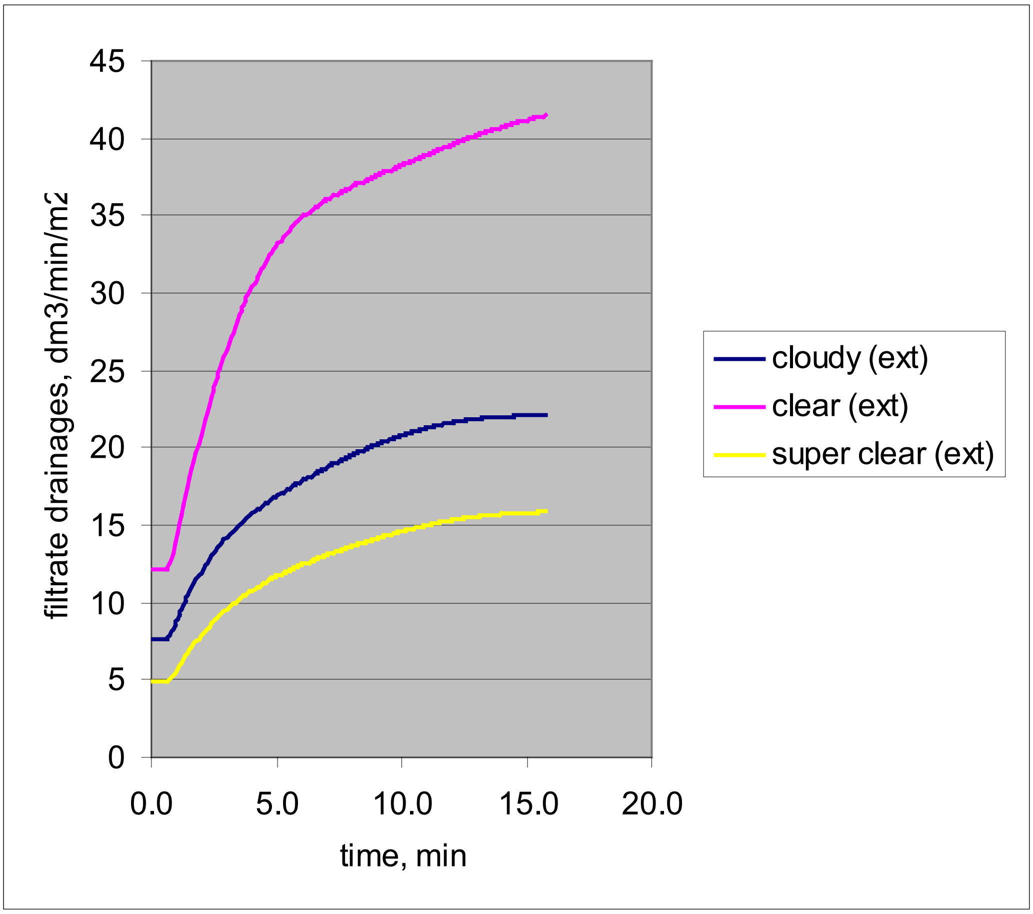

Figure 29 A step change in the white water feed and a step response of the drainages of filtrates calculated by the disc filter external model. The feed changed from 30 kg/s to 110 kg/s and the control system changed the rotational speed from 0.52 rpm to 1.46 rpm. The angle of offset was 60° and disc submerge was 65%. Cloudy filtrate was recycled back to the filter. The results were simulated with APMS. The simulated filter had 12 discs and a total area of 168 m^2.

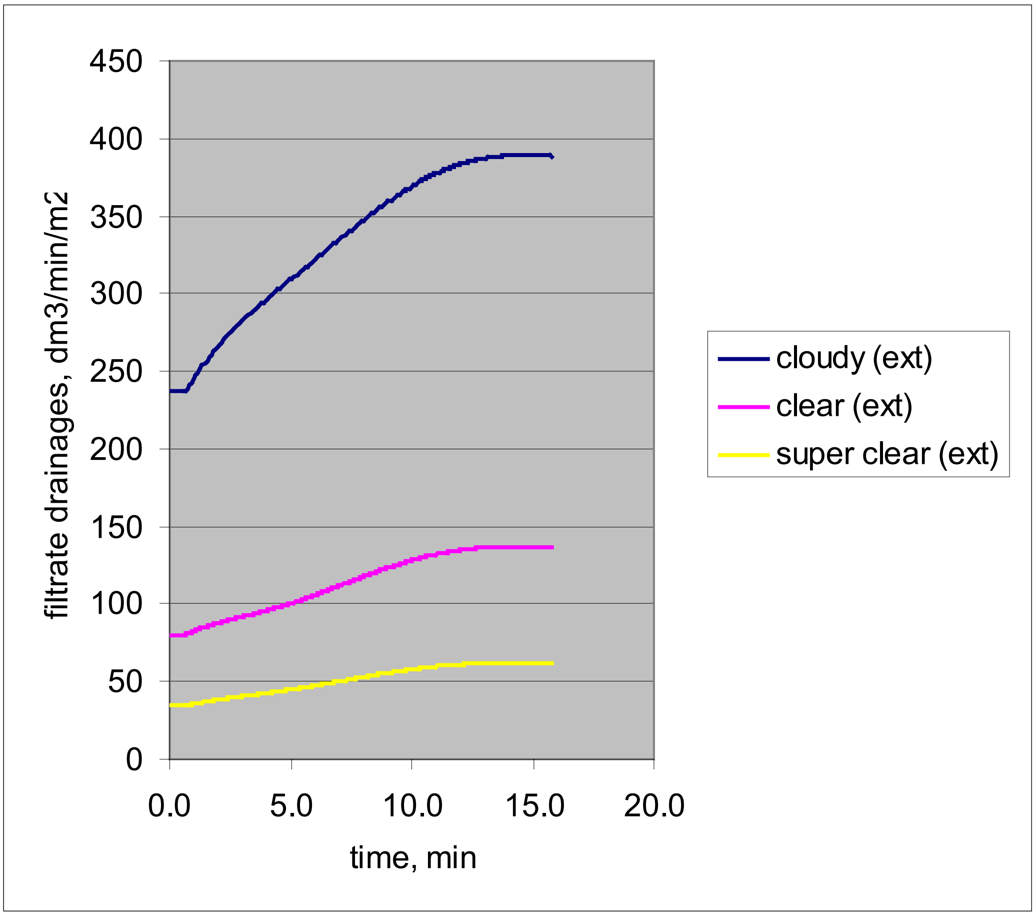

Figure 30 A step change in white water feed and a step response in consistencies for filtrates calculated by the disc filter external model. The feed changed from 30 kg/s to 110 kg/s and the control system changed the rotational speed from 0.52 rpm to 1.46 rpm. The angle of offset was 60° and disc submerge was 65%. Cloudy filtrate was recycled back to the filter. Results were simulated with APMS. The simulated filter had 12 discs and a total area of 168 m^2.

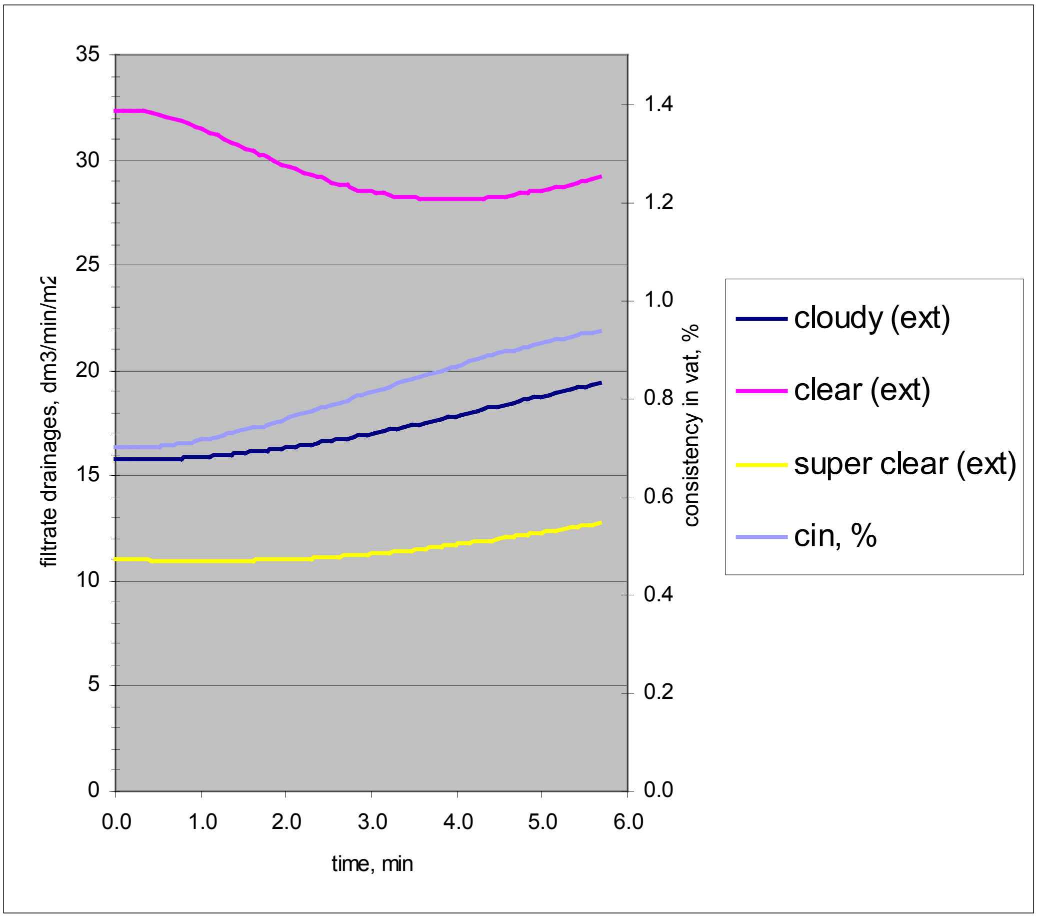

Figure 31 The inlet consistency was changed by the sweetener feed controller. The figure shows the response of the filtrate drainages calculated by the disc filter external model. The white water feed was 95 kg/s and the control system changed the rotational speed from 0.9 rpm to 1.2 rpm. The angle of offset was 60° and disc submerge was 65%. Cloudy filtrate was recycled back to the filter. The results were simulated with APMS. The simulated filter had 12 discs and atotal area of 168 m^2.

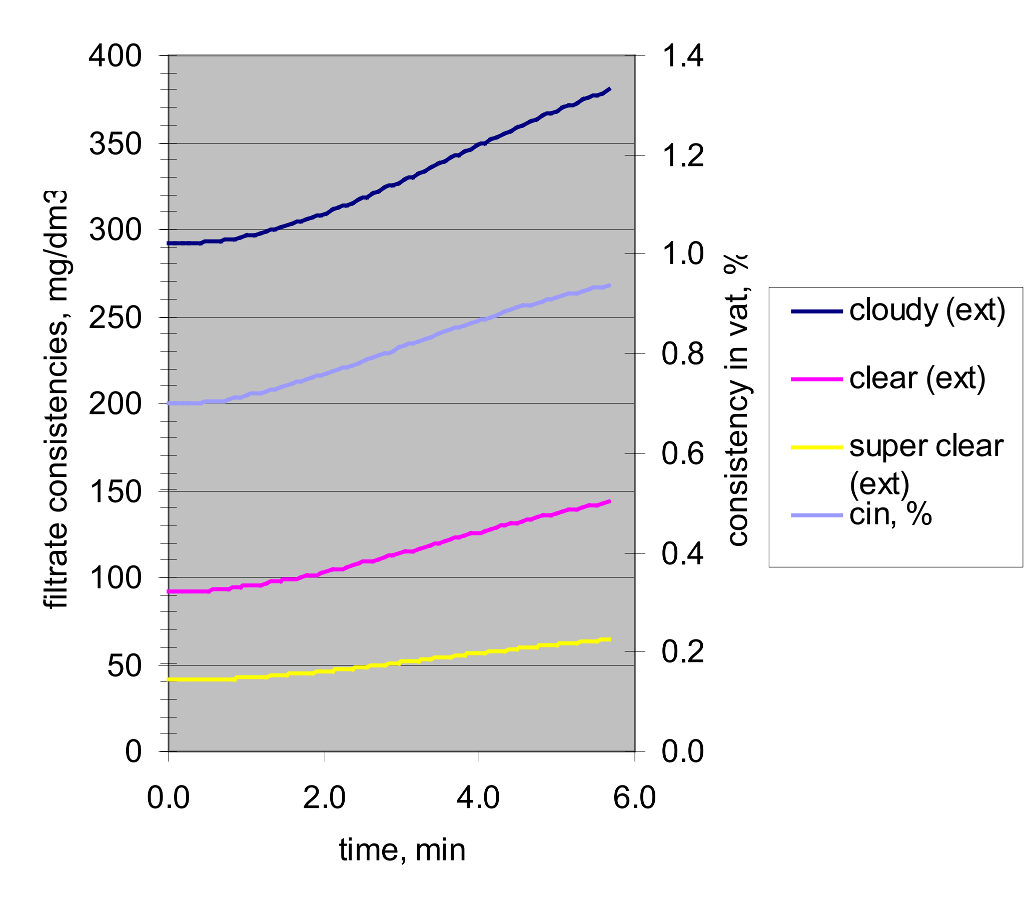

Figure 32 The inlet consistency was changed by the sweetener feed controller. The figure shows the response of the filtrate consistencies calculated by the disc filter external model. The white water feed was 95 kg/s and the control system changed the rotational speed from 0.9 rpm to 1.2 rpm. The angle of offset was 60° and disc submerge was 65%. Cloudy filtrate was recycled back to the filter. Results were simulated with APMS. The simulated filter had 12 discs and a total area of 168 m^2.

5.4.3 Response Comparisons between the Original and New Model

It was not possible to run exactly the same tests with the original model, since it did not contain freeness and angle of offset. Tests were run for rotational speed change from 0.6 rpm to 1.5 rpm and inlet consistency change from 0.7 % to 0.9 %. Results are in Figures 33-39.

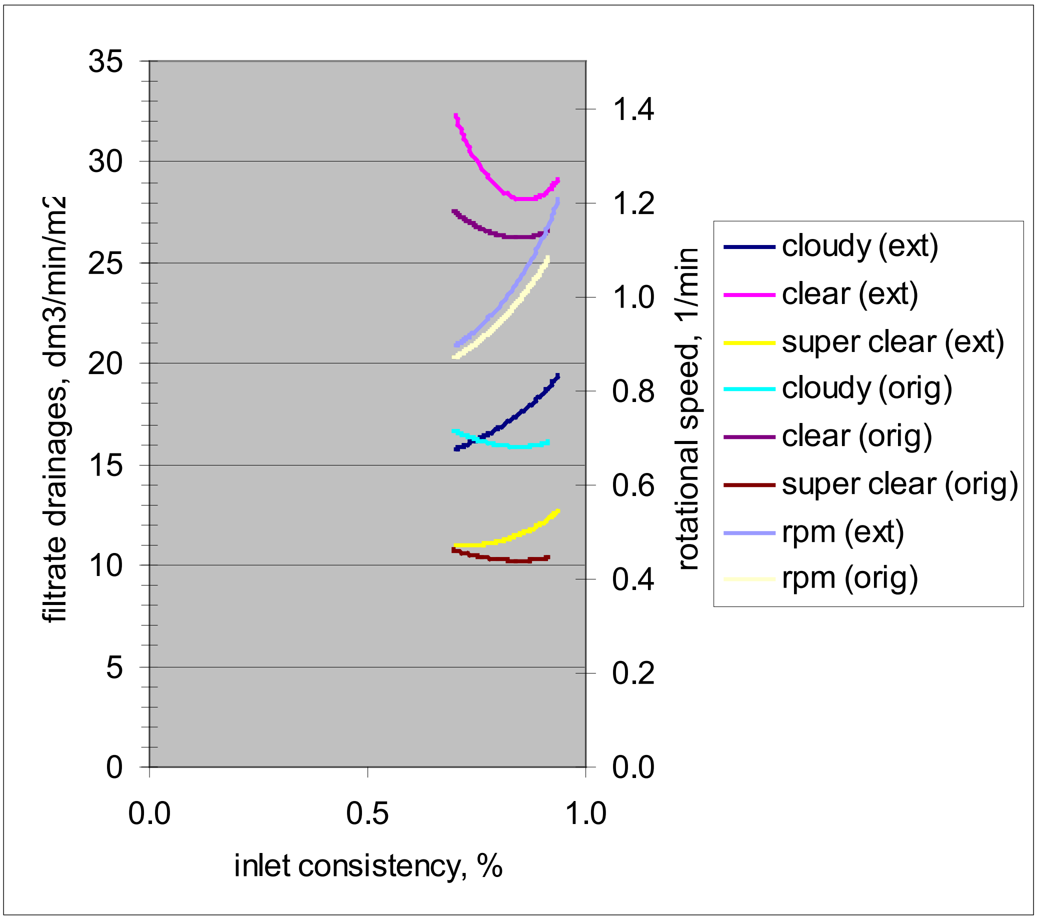

Figure 33 The inlet consistency was changed by the sweetener feed controller. The figure shows response of the filtrate drainages calculated by the disc filter external model and the original model [1]. The white water feed was 95 kg/s and the control system changed the rotational speed from 0.9 rpm to 1.2 rpm. The angle of offset was 60° and disc submerge was 65%. Cloudy filtrate was recycled back into the filter. Results were simulated with APMS. The simulated filter had 12 discs and a total area of 168 m^2.

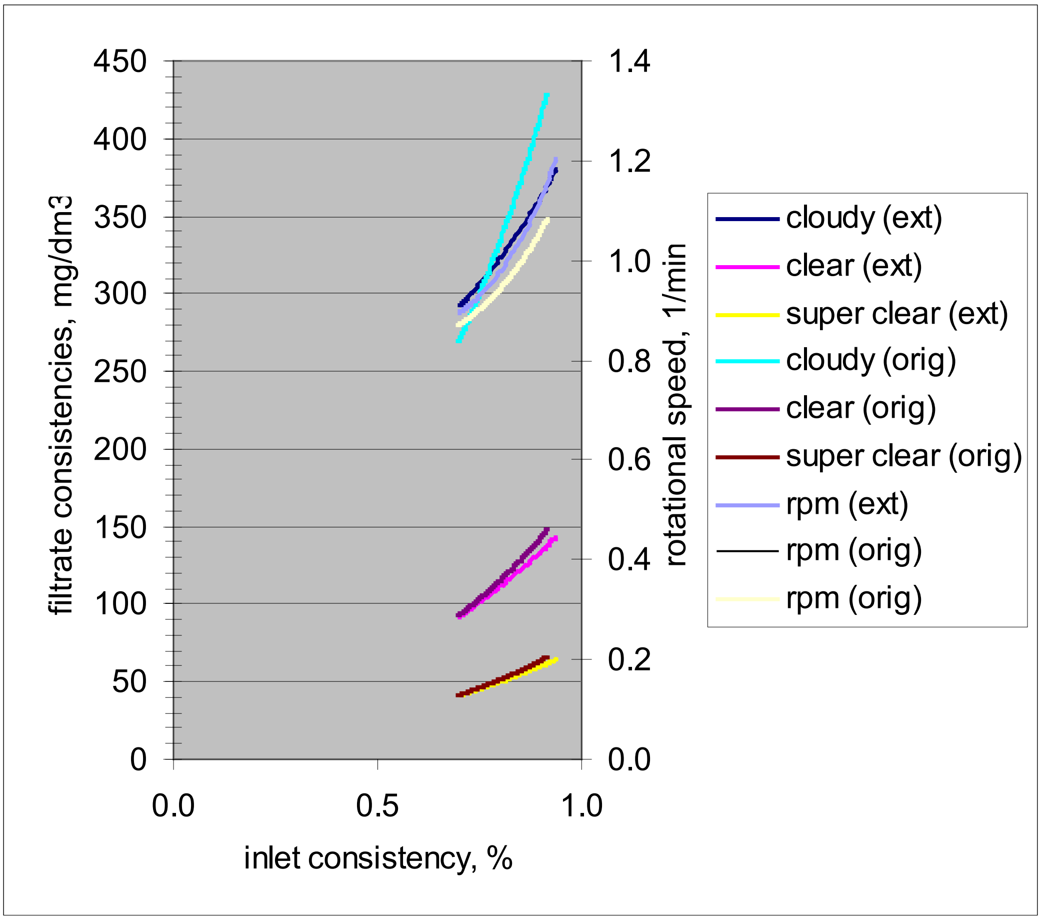

Figure 34 The inlet consistency was changed by the sweetener feed controller. The figure shows response of the filtrate consistencies calculated by the disc filter external model and the original model [1]. The white water feed was 95 kg/s and the control system changed the rotational speed from 0.9 rpm to 1.2 rpm. The angle of offset was 60° and disc submerge was 65%. Cloudy filtrate was recycled back into the filter. Results were simulated with APMS. The simulated filter had 12 discs and a total area of 168 m^2.

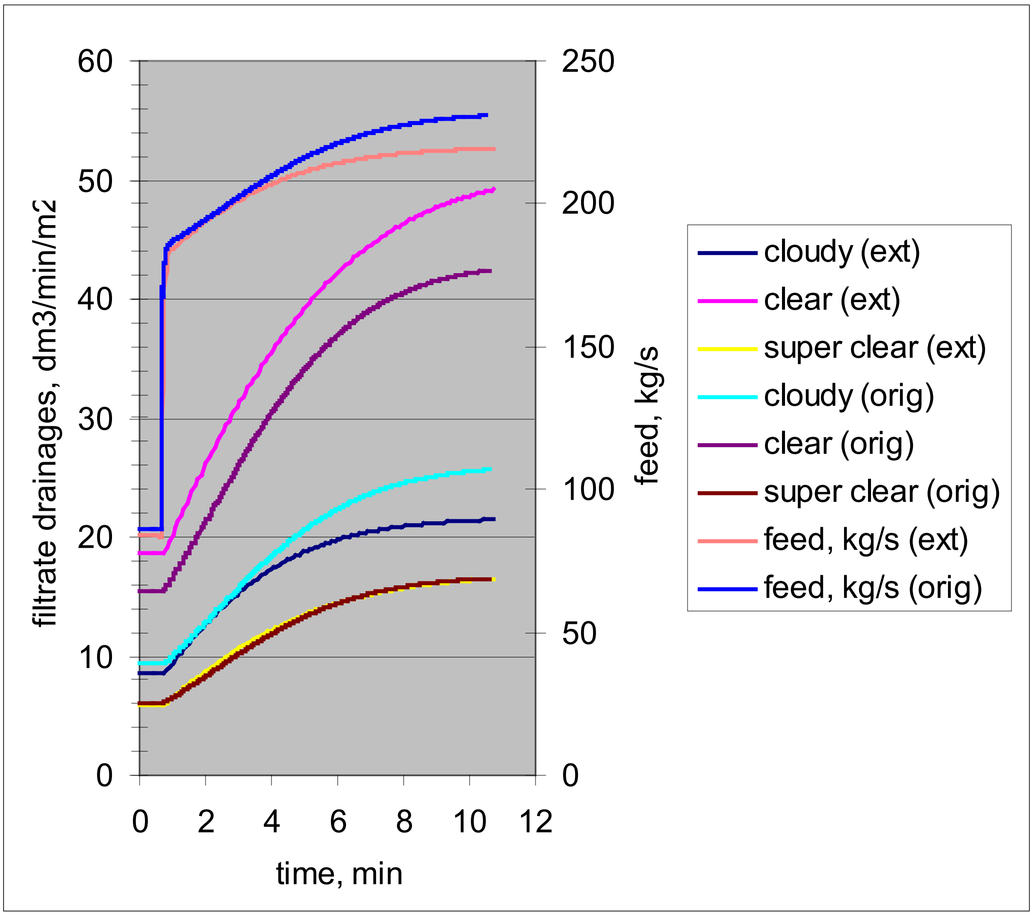

Figure 35 A step change in white water feed from 60 kg/s to 160 kg/s. The figure shows the response of the filtrate drainages calculated by the disc filter external model and the original model [1]. The angle of offset was 60° and disc submerge was 65%. The vat consistency controller was disabled and no sweetener was added. The white water consistency was 1.0 %. Cloudy filtrate was recycled back to the filter and diluted the inlet consistency into 0.7-0.8 %. Results were simulated with APMS. The simulated filter had 12 discs and a total area of 168 m^2.

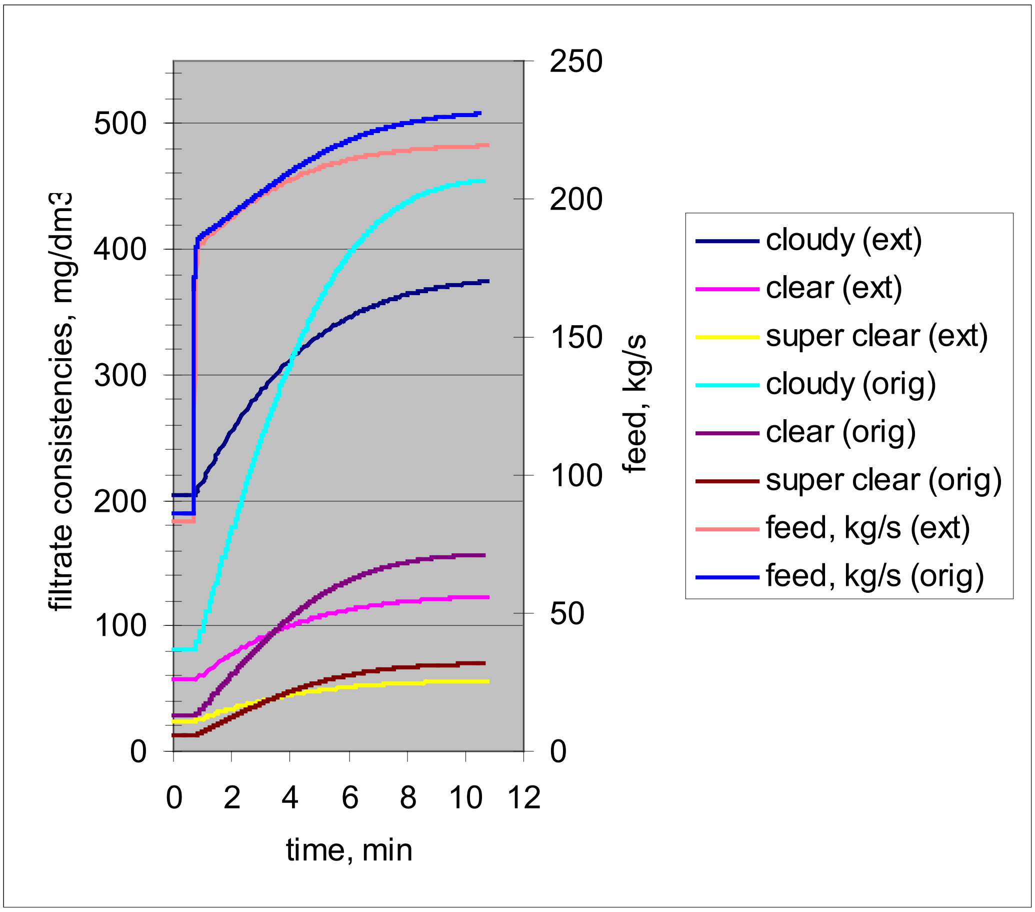

Figure 36 A step change in white water feed from 60 kg/s to 160 kg/s. The figure shows the response of the filtrate consistencies calculated by the disc filter external model and the original model [1]. The angle of offset was 60° and disc submerge was 65%. The vat consistency controller was disabled and no sweetener was added. The white water consistency was 1.0 %. Cloudy filtrate was recycled back to the filter which diluted the inlet consistency into 0.7-0.8 %. Results were simulated with APMS. The simulated filter had 12 discs and a total area of 168 m^2.

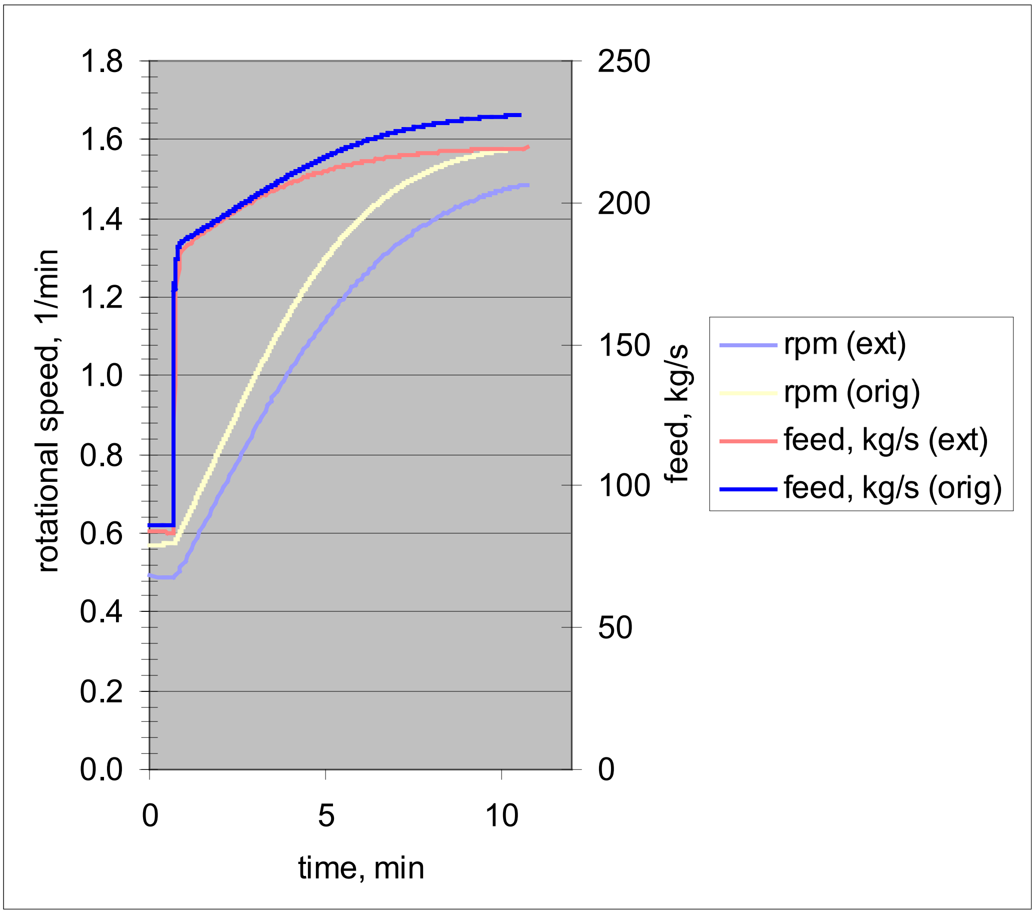

Figure 37 A step change in white water feed from 60 kg/s to 160 kg/s. The figure shows the response of the rotational speed by the disc filter external model and the original model [1]. The angle of offset was 60° and disc submerge was 65%. The vat consistency controller was disabled and no sweetener was added. The white water consistency was 1.0 %. Cloudy filtrate was recycled back to the filter which diluted the inlet consistency to 0.7-0.8 %. A rotational speed controller that kept the liquid level in the vat constant changed the rotational speed of the discs. Results were simulated with APMS. The simulated filter had 12 discs and a total area of 168 m^2.

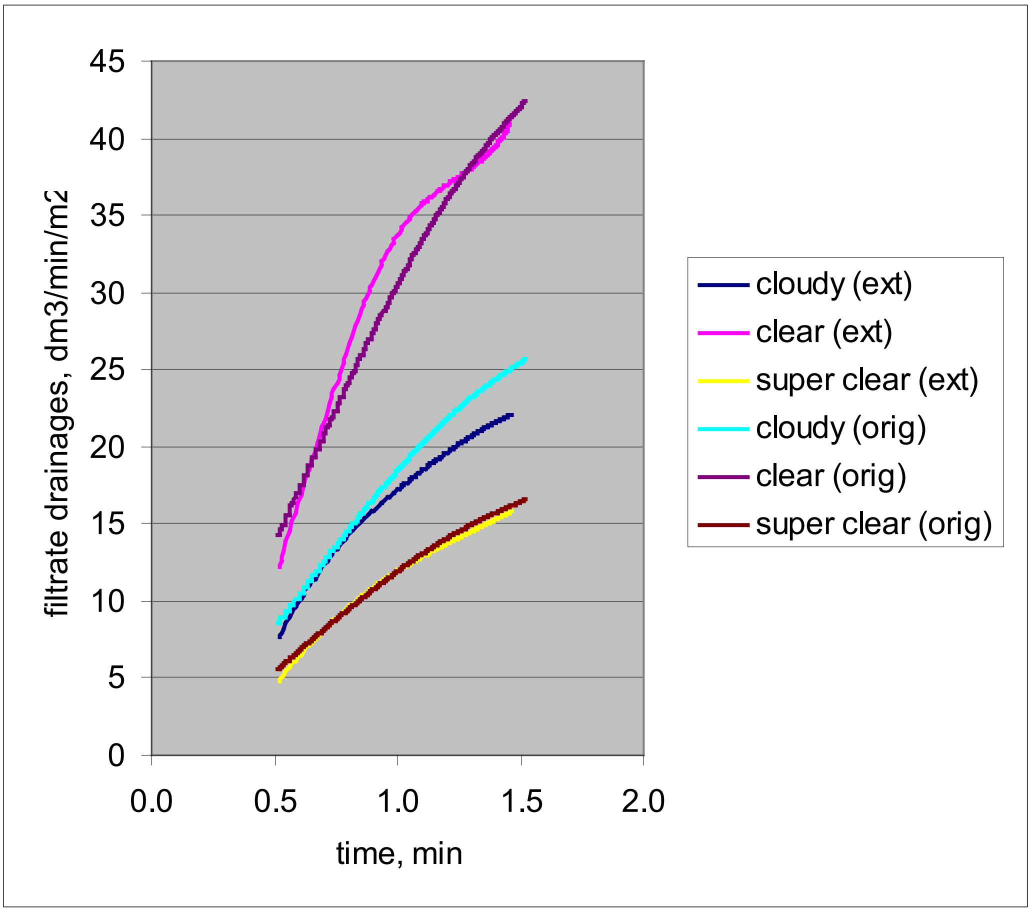

Figure 38 A step change in white water feed from 60 kg/s to 160 kg/s. The figure shows the response of the filtrate drainages calculated by the disc filter external model and the original model [1]. The angle of offset was 60° and disc submerge was 65%. The white water feed consistency was 0.3 %. Cloudy filtrate was recycled back to the filter which diluted the inlet consistency to 0.2 %. The consistency in the vat was controlled by the amount of sweetener added to the feed. The controller kept the consistency at 0.8 %. Sweetener consistency was 5.0 %. Results were simulated with APMS. The simulated filter had 12 discs and a total area of 168 m^2.

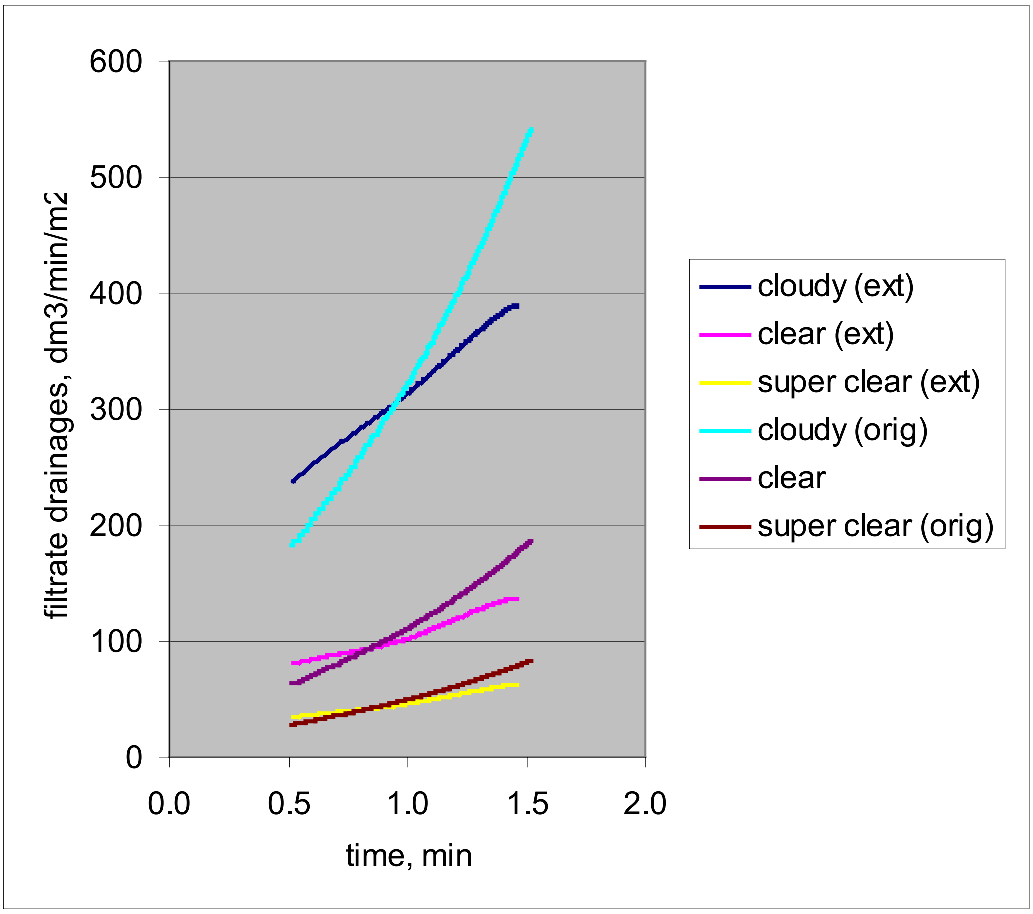

Figure 39 A step change in the white water feed from 60 kg/s to 160 kg/s. The figure shows the response of the filtrate consistencies calculated by the disc filter external model and the original model [1]. The angle of offset was 60° and disc submerge was 65%. The white water feed consistency was 0.3 %. Cloudy filtrate was recycled back to the filter which diluted the inlet consistency to 0.2 %. The consistency in the vat was controlled by the amount of sweetener added to the feed. The controller kept the consistency at 0.8 %. The sweetener consistency was 5.0 %. Results were simulated with APMS. The simulated filter had 12 discs and a total area of $168 m^2$.

6 Discussion

6.1 Disc Filter Model Parameterisation with Gallery

The disc filter model in APMS has some rather exotic parameters that are now easier to find with the help of Gallery. Filtration area was originally determined by giving the number of discs, disc diameter and the diameter of the central shaft to the model, which then calculated the filtration area. This was changed so that now the model contains a field where the user can enter the total filtration area of the filter. The old and more laborious way is still implemented and the user can choose which one he wants to use.

There are six parameters determining the filter geometry that can be a little awkward to find:

- Feed height from the filter bottom
- Overflow height from the filter bottom
- Fibre shaft height from the filter bottom
- Pressurised air inlet height
- Mat removal water inlet height
- Disc washing water inlet height

A dimensional drawing is included in the type definition of the disc filter. Pipe positions can be found from it. Without the Gallery this kind of information would be difficult to attain.

The original disc filter model requires a nominal point for rotational speed. The user gives nominal drainages and consistencies for each filtrate and also nominal total feed at this rotational speed. A straight line is drawn from zero revolutions per minute via the nominal point for each drainage and consistency. Determining the nominal point is difficult, since there is very little information concerning disc filter measurements that can be found from literature. The equations created in this work serve as a tool with which the user can calculate nominal points for disc filter operation, should he choose to use the original model.

6.2 Results Without Simulation Program

Total filtrate flow, cloudy, clear and super clear filtrate fluxes and consistencies can be found in Figures 10-16. When a designer wants to know how the disc filter behaves for a certain type of production, he first searches the freeness of the sweetener type. Let freeness be 300 ml CSF. Normally the inlet consistency is near 0.8 % and rotational speed of the filter changes between 0.5-1.5 rpm. Angle of offset is usually either 60° or 40°. From the figures he can quickly see how much drainage he is going to get and what are the consistencies of the filtrates. With the Equation (21) and Table II, the designer can get a fair understanding on the filter about the boundary conditions of Table III.

Since the original model calculates the amount and consistency of the pulp, the external model only gives drainages and consistencies and lets the simulation program calculate the mass balance. If the designer wants to know how much feed the filter needs and how much thickened pulp he is going to get from the filter, he has to do some balance calculations. The model is kind of the reverse of the normal procedure. Whereas usually white water and sweetener feed are known and the amount of pulp can be estimated, the external model lets the simulation program do the maths for the balance. It is after all meant to be a part of the simulation program.

6.3 Simulation Results with Step Changes

6.3.1 Rotational Speed Step

Figure 18 shows how the filtrate drainages change if the rotational speed is increased from 0.5 rpm to 1.0 rpm. A quick step response for each of the drainages follows. As the filter rotates faster, it also gives bigger flows. The responses are clearly too quick. A perfect step for the disc filter can be easily simulated. There seems to be no inertia in the discs. In a real situation it would not happen instantly. In this experiment the automatic control system for the filter speed was obviously turned off. It is possible to assign manually a value for the rotational speed, which will then be implemented in the next time step. In this case after 0.2 s. APMS recorded the state of the process when five seconds has passed and therefore the slope of the step was not a perfect 90°, but less. With a rotational speed controller the curves would be more realistic. Figure 37 shows how the speed controller increases rotational speed after a step change is made to the feed.

Figure 19 shows the filtrate consistencies after a rotational speed step. All the consistencies rise as the rotational speed rises. The response is consistent with reality, since if the filter rotates faster, the cake gets thinner and therefore the filtrates are less clean because the cake cannot apprehend as much solids.

Manufacturer comments: Drainages look good, but consistency results are too pessimistic. If the clear filtrate has a consistency above 100 ppm, nozzles will be blocked. Cloudy concentration should be 275-400 ppm, clear 30-60 ppm and super clear 20-40 ppm.

6.3.2 Inlet Consistency Step

Figure 20 shows how the filtrate fluxes change after a step change in the inlet consistency. Figure 21 shows the consistencies after the same change. The changes are not nearly as fast as in the previous experiment. This is because cloudy filtrate is recycled back to the feed and it dilutes the feed so that the vat consistency changes a lot slower and to a lesser degree, as can be seen from Figure 24. The consistencies rise after there is an increase in the inlet consistency, but the drainages behave less expectedly. The inlet consistency step simulation results were made again to show the effect of the rotational speed controller. The drainages in Figure 22 and consistencies in Figure 23 behave much like in the earlier experiment. Since the speed controller increases rotational speed of the filter as consistency starts to rise, both drainages and consistencies rise, which is a more realistic response to the inlet consistency step.

The reason why clear filtrate flow drops quite dramatically after an increase in the inlet consistency is in the model and its coefficients. The measurements that GL&V make for their filters describe a percentage of each filtrate. In the original model these percentages are fixed. The user gives angles for each event, such as cloudy filtrate between 45° and 65°, clear and super clear respectively, disc washing etc. In the external model percentages of each filtrate are calculated using the same four variables as elsewhere in the model. The percentages add up quite near to 100%, but to ensure that, the external model evens the percentages so that the clear filtrate percentage is 100% - cloudy percentage - super clear percentage.

Manufacturer comments: Decrease of cloudy filtrate too drastic, but clear and super clear drainages show more visible decrease. Consistencies are a bit too high in general. With the rotational speed control the results are more realistic.

6.3.3 Freeness Step

Figure 25 shows that filtrate consistencies rise after freeness rises. The amount of filtrate gathered is directly proportional to how big the freeness is. The results are consistent with a real situation.

Figure 26 is realistic. As the freeness increases, it contains less beat fibre that is more readily apprehended by the filter media. The filtrate consistencies drop as freeness increases.

Manufacturer comments: The proportional changes are accurate for both drainages and consistencies. Cloudy consistency should perhaps drop more. Consistencies are a bit too high in general.

6.3.4 Angle of Offset Step

GL&V uses a parameter called the *angle of offset* to adjust the ratio between cloudy and clear filtrate. It was originally not intended to be implemented in the model, but since it rather dramatically affects the filtration, it was added. Figure 27 shows that if the angle is dropped from 60° to 40°, clear and super clear drainages rise but cloudy drainage drops. The angle measures how wide the sector that collects cloudy filtrate is compared to clear filtrate.

In Figure 28 very little effect can be seen in the consistencies of the filtrates. This is disappointing, since the angle of offset should have a bigger effect on the consistencies. If the angle is dropped and the proportion of cloudy filtrate is decreased, the filtrate should be thicker. Its consistency does increase, but not considerably. There is no change in clear filtrate consistency.

Manufacturer comments: The change in drainages is very realistic, but clear filtrate consistency should react more. It should rise like the cloudy did. The negligible effect on the super clear filtrate consistency is expected.

6.4 Simulation Results for a Full Control System

6.4.1 White Water Feed Step

This test was run with both the consistency controller and liquid level controller. After the white water feed was increased, stock in the vat was diluted and hence the consistency controller increased the feed of the sweetener and vat level controller speeds up to the rotational speed. Figure 38 shows the comparison of the drainages resulting from a step change in white water feed between the original model and external model. Both of the models gave similar results for super clear drainages. The difference between cloudy drainages was also less than 15 % for both models, the external model gave a smaller amount of drainage. Clear drainage looks more interesting, since the external model gave a much more curved response than the original one. It reacted more heavily to the consistency oscillation that occurred when the white water feed was increased. Both are quite close to each other.

Figure 39 shows the differences between the filtrate consistencies. A very big difference can be seen in cloudy drainage. The curves coincide near to 0.9 rpm which is the nominal point for the original model. Similar differences can be found for clear and super clear consistencies. GL&V says that the external model gives more accurate consistency simulation.

Manufacturer comments: The changes in drainages are realistic, though cloudy and clear filtrate should rise a bit more than they do. Clear filtrate looks very good. The consistencies are again too high, but the proportional changes are realistic.

6.5 Comparisons between the Original and External Model

6.5.1 Inlet Consistency Change

Figure 31 shows how drainages behave if the consistency controller increases consistency in the vat. Increase in consistency is executed by adding more sweetener to the feed stream. As the consistency starts to climb, the amount of clear filtrate starts to drop, because a thicker cake is formed. It has little effect on cloudy and super clear filtrates. This causes an increase in the vat liquid level and therefore the rotational speed controller increases the rotational speed. Increased sweetener feed (which means increased overall liquid feed) and increased rotational speed results in all the filtrates eventually starting to climb up the drainage scale, though thicker stock is added to the filter.

Figure 32 shows an increase in filtrate consistencies as the consistency of feed increases.

Manufacturer comments: The curves show how the disc filter behaves in practice. Dynamic simulation of control systems reveals how the process lives. Customers may not always understand that increasing consistency can increase capacity, because they do not take into account that rotational speed is increased because of increased sweetener feed and that increases the total capacity. Consistencies are again too high. Clear filtrate should start from 30-50 ppm and super clear from 20-40 ppm. Now they start from 90 ppm and 40 ppm.

Figure 33 contains a comparison between the original model and the external model. It shows the results for the same experiment as the previous two figures but plotted against inlet consistency instead of time. There is quite a lot of information in the figure. Drainages for different filtrates and rotational speed are presented for both models.

Figure 34 contains the same comparison between two models. It shows the consistencies calculated by both of them. There is a clear difference in cloudy consistency. Clear and super clear consistencies are almost identical.

Manufacturer comment: The original (linear) model gives more realistic drainages, but the consistency of cloudy filtrate is estimated better with the external model.

6.5.2 Step Change in the White Water Feed

In this experiment the white sweetener feed was removed and the white water consistency was set at 1.0 %. The cloudy filtrate recycle diluted the feed to 0.7-0.8 %. Figure 35 shows a considerable difference between the external and original model. The external model gives a much higher clear drainage and a somewhat lower cloudy drainage compared to the original model. The feed is almost identical for both cases, since cloudy filtrate drainage, which is recycled back to the filter, is not very different.

In Figure 36 a very big difference in cloudy consistency can be seen. The original model gives totally different results to the new model. Figure 37 shows that there is a difference in rotational speed between the models. The difference remains almost constant throughout the experiment.

Figure 38 shows results for the same experiment against rotational speed. Clear filtrate drainage behaves more restlessly in the external model than in the original model. The curves should coincide at 0.9 rpm, but since there is a different amount of recycled cloudy filtrate, the feed is diluted differently in both models, rotational speed is a bit different and therefore only the super clear filtrate can be seen to coincide correctly.

Figure 39 shows clearly the difference between the two models. The original model draws a linear function from zero via the nominal point, whereas the external model draws individual non-linear curves and needs no nominal point formatting before simulation can be started.

Manufacturer comment: The consistencies are calculated much better with the external model.

6.6 Suggestions for Further Development

- There is a scope in the model for optimisation. The source code is not examined close enough from performance point of view.
- Besides fibre there is also a considerable amount of ash in the white water feed. Ash penetrate the filter medium easily and accumulate in the paper mill water cycle. The model does not calculate how well ash is removed from the water.
- Different filter types should be taken into consideration in further development. Different types of production are even more important. Even though freeness determines much of how the filter behaves, it still is a very rough estimate of the production type. Mass mixes are common in paper mills. The model does not have any tools that could calculate how for example two different masses behave, if they are fed to the filter and what is be the combined freeness of the mixture.
- Suction legs are of equal length and diameter. In reality all the legs can be different and that could be added to the model.
- The model should be able to simulate startup like the original model. Now the model has boundary values that do not allow the rotational speed to go below 0.5 rpm.

6.7 Conclusions

If a literary search is carried out on disc filter studies, not many references can be found. Studies on disc filter simulation models are even fewer. Disc filter is sometimes called “the forgotten device” of a paper mill. The model [1] and the disc filter external model created in this study add value to the new integrated simulation and design environment (the Gallery project) and increase the availability of disc filter simulation tools for process designers. Now there is a tool that allows disc filter users to see the filter in a dynamic simulation environment before even consulting the manufacturer.

The external model is flexible and it can be altered if needed. Now that the original model is modified so that it may utilise external models, any filtration curves may be added to the model with little modification in the code.

One could argue that the model is too complex and it may behave unexpectedly in certain process conditions. Indeed, a linear model would have given quite similar results with little worries concerning unexpected changes in the curves. The original model was linear so it was quite reasonable to make a more complex non-linear model, since filtration curves for rotary disc filters are usually not linear, but curved.

The original model also needed nominal point formatting based on measurements, calculations or estimates before the simulation could be started. The external model removes this need. The total filtration area was too laborious to put into the original model and it is now simplified. Freeness has been added to the original model. The disc filter model is much more flexible now than it was before.

The figures show that almost all of the responses to various upsets were correct. Qualitative responses were more correct, but some quantitative responses may need adjustment. The proportional changes in drainages and consistencies were generally quite good, though few of the absolute values were not entirely accurate. The external model gave in most cases a better estimate for the drainages and consistencies than the original one. Consistencies were too high in general, but the problem was be fixed by tuning the parameters of the model or by creating different equations for cases that caused problems. The manufacturer was pleased with the results. The model met their requirements from a general point of view.

List of Sources

1. Savolainen, J., Kiekkosuodattimen dynaaminen malli, Diplomityö, Teknillinen korkeakoulu, Kemiantekniikan osasto, Espoo 1999, Finland, 100p.
2. International Conference on Process Integration, Copenhagen, Denmark, 7-10 March 1999, Conference Proceedings, Volume I, Papers, p. 7.
3. Söderman, J., Prosessi-integraation avulla arvoketjujen hallintaan, Prosessi-integraatioteknologiaohjelma, TEKES vuosiraportti 2000, Finland
4. Karhela, T., Prosessi-integraation tieto- ja malligalleria, Prosessi-integraatioteknologiaohjelma, TEKES vuosiraportti 2000, Finland
5. McCabe, W.L., Smith, J.C., Harriot, P., Unit Operations of Chemical Engineering, McGraw-Hill Book Co., Singapore, 1993, 1130 p.
6. Wakeman, R.J., Tarleton, E.S., Filtration Equipment Selection, Modelling and Process Simulation, 1st edition, Elsevier Advanced Technology, Oxford 1999, 446 p.
7. Kovasin, K., Mekaanisten massojen saostus ja puristus, Mekaanisen massan käsittely eri paperilajien valmistuksessa, INSKO 213-88, Finland 1988.
8. Göttsching, L., Pakarinen, H., Recycled Fiber and Deinking, Gummerus Printing, Jyväskylä, Finland 2000, 649 p.
9. Smook, G.A. and Kocurek, M.J., Handbook for Pulp & Paper Technologists, 7th Ed., Canada, 1989, 395 p.
10. Available: http://knowpap.vtt.fi
11. Pitkänen, M., GL&V Finland, Oral statement 8.10.2001.
12. Available: http://www.aspentech.com/ap/downloads/aspenplus.pdf
13. Available: http://quorum.simsci.com/comm/commprod.nsf/PROII?openview
14. Available: http://www.chemstations.com/products/chemcad1.pdf
15. Depew, C.A., Nielsen, R.B., Dynamic simulation for process design, Hydrocarbon processing, July 1996, p. 67.
16. Warren, S.D., Seader, J.D., Lewin, D.R., Process Design Principles Synthesis, Analysis and Evaluation, USA, 1999, 824 p.
17. Silvennoinen, E., APROS Program Development System, Programmer's Guide, Version 1.6, 1990