LEARNING HOW TO USE THE FILTRATION PROGRAM FILOS BY SOLVING REAL PROJECTS STEP BY STEP AND UNDERSTANDING THE HIGH USAGE POTENTIAL OF THE PROGRAM

Project 1:
Scale-Up and Optimization of a Belt Filter based on ONLY 2 Laboratory Filtration tests (Buchner Tests)

In your production unit you have the task to install a new continuously working filter and optimize its operation for the filtration of a suspension created after a crystallization process. This suspension (we call it with the name "Proj1") has the following filtration related characteristics:

Viscosity of mother liquid:	2.2 mili Pa s
Density of mother liquid:	800 kg/m^3
Density of Solids:	1527 kg/m^3
Susp. solids mass fraction Cm	16%

The filter cake has to be washed after the cake formation step and then deliquored. The washing liquid has the following parameters:

Viscosity of the washing liquid: 0.58 mili Pas
Density of the washing liquid: 791 kg/m^3

Your requirements regarding the filter performance are the following:

- Solids throughput (dry solids): 2500 kg/h
- Cake moisture content of the discharged cake: <12%
- Wash out content in the cake x=X/X0: < 1%

You contacted a filter manufacturer company. This company took a sample and they did 2 experiments with a laboratory Buchner-filter (see results in table 1).

Table 1:

Exp. Nr.	Δp/bar	Vsus/l	hc/mm	tf/s	td/s	Ms/g	Rf/%
1	0.28	2.354	28	200	60	326.2	56.8
2	0.65	2.158	20	55	60	299	13.3

Filter area of the Buchner Filter A: 269 cm^2

Based on the test results (see table 1) they proposed you a belt filter with the following geometrical and setting data:

Filter area:	10 m^2
Belt width:	1 m
Length for cake formation:	4 m
Length for cake washing:	1.5 m
Length for cake deliquoring:	3 m
Pressure Difference:	0.7 bar
Belt speed:	3 m/min
Wash liquid consumption:	1.5 l/kg dry solids

Based on the laboratory filtration test results and with the above geometrical and setting parameters of the Belt filter the filter manufacturer gave you a guarantee for your requirements (dry solids throughput: 2500 kg/h, cake moisture content Rf<12 % and wash out content in the cake x=X/X0<1% (X= the real amount of wash out content in the cake per kg dry solids and X_0 the maximal amount of wash out content in the cake that means we have X_0 directly after finishing the cake formation step (cake saturated with mother liquid).

Your Tasks

Task 1

It is your first and main task to check by using the FILOS program if the guarantee of the manufacturer is correct.

Task 2

Which setting parameters you should preferably change to achieve a higher solids throughput without negative effects in the cake moisture content and the washing efficiency?

Task 3

What setting parameters you should change if you want to have significant changes in the cake moisture content?

Task 4

Considering the possibility of a production increase (new solids throughput= 4000 kg/h) what filter size you should purchase to be able to have also this increased productivity if the cake height shouldn't be smaller than 25 mm, the moisture content and the wash liquid consumption should be the same as the original design with the lower solids throughput. What is the required area division for cake formation, washing and deliquoring if 95% of the total area can be used for these steps and which the belt speed?

Task 5

If you have decided for the bigger filter size (A=20 m^2) in order to consider the possible production increase then which settings you should have for the current requirements (solids throughput 2500 kg/h)?

Task 6

Is the pre thickening of the cake instead of purchasing a bigger filter size also a reasonable choice? Explain why?

Task 7

To judge if the selected filter medium regarding filter capacity is for this application the correct one you asked the manufacturer to give you the determined filter medium resistance. Why the manufacturer can not give you this value? What tests are necessary and how they should be carried out to have a reliable value of the filter medium resistance?

Task 8

- Do you think that the determination of the cake compressibility is for this case and the given apparatus possible? Why the determination of the cake compressibility is in this case not necessary?

Solutions Project 1

Scale-Up and Optimization of a Belt Filter based on only 2 Laboratory Filtration tests (Buchner Tests)

Task1:

It is your first and main task to check by using the FILOS program if the guarantee of the manufacturer is correct:

- Solids throughput (dry solids): 2500 kg/h
- Cake moisture content of the discharged cake: <12%
- Wash out content in the cake $x=X/X_0$: < 1%

We have to use the option *Standard Calculation* for the Continuous Belt Filter using the following geometrical and setting data (please notice that the *Standard Calculation* option is used when we have the filter geometry as input and we want to calculate the Filter performance):

Given filter geometry and settings data

Filter area:	10 m^2
Belt width:	1 m
Length for cake formation:	4 m
Length for cake washing:	1.5 m
Length for cake deliquoring:	3 m
Pressure Difference:	0.7 bar
Belt speed:	3 m/min
Wash liquid consumption:	<1.5 l/kg dry solids

Given suspension material parameters

Viscosity of mother liquid:	2.2 mili Pa s
Density of mother liquid:	800 kg/m^3
Density of solids:	1527 kg/m^3
Susp. solids mass fraction Cm	16%

Given wash liquid parameters

Viscosity of the washing liquid:	0.58 mili Pas
Density of the washing liquid:	791 kg/m^3

We go to the Continuous Belt Filter-*Standard Calculation* option and we enter what we have:

Please notice:

Length of the Belt filter:

$L=A/B=10\ m^2/1m= 10\ m$

$af=Af/A=Lf/L= 4/10= 0.4$

$aw=Aw/A=Lw/L=1.5/10=0.15$

$ad=Ad/A=Ld/L=3/10=0.3$

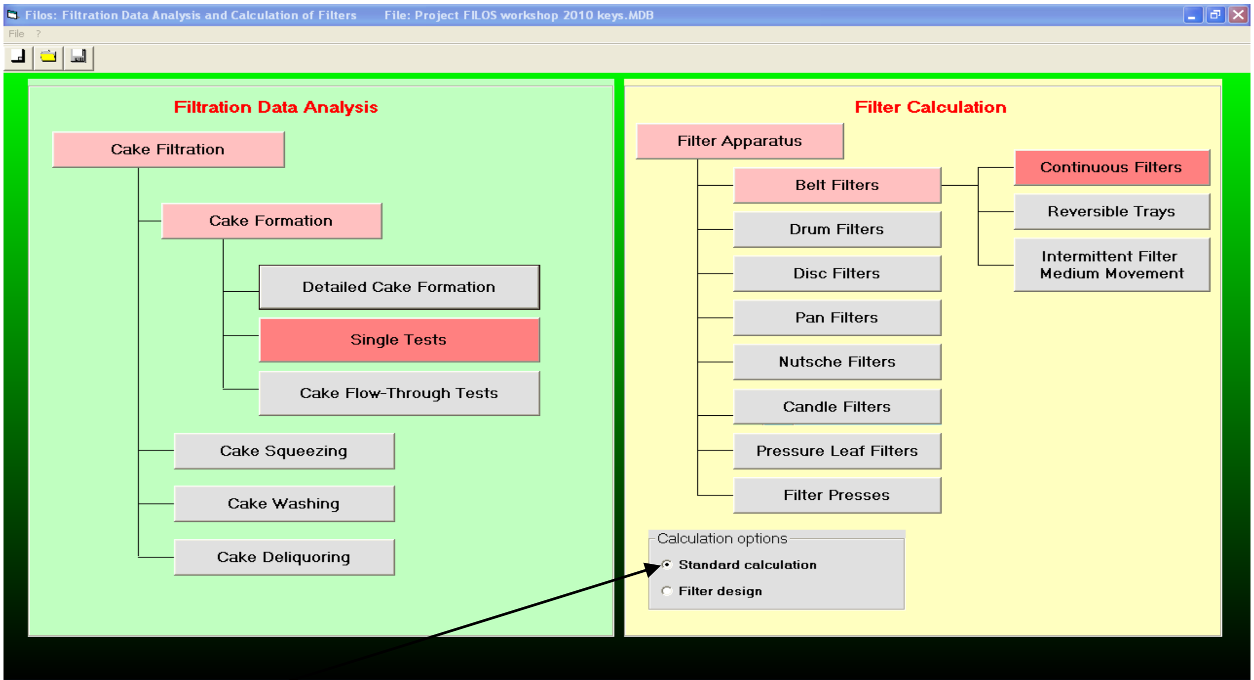


Fig. 1: From the FILOS –Start window click the Button *Filter Apparatus* → *Belt Filters* → *Continuous Filters* (Option: *Standard calculation*: This option is the default one and is used when the filter is given and the performance of the filter has to be calculated. The Option *Filter Design* is for the cases when the performance is given and the necessary filter geometry and filter setting parameters have to be determined.

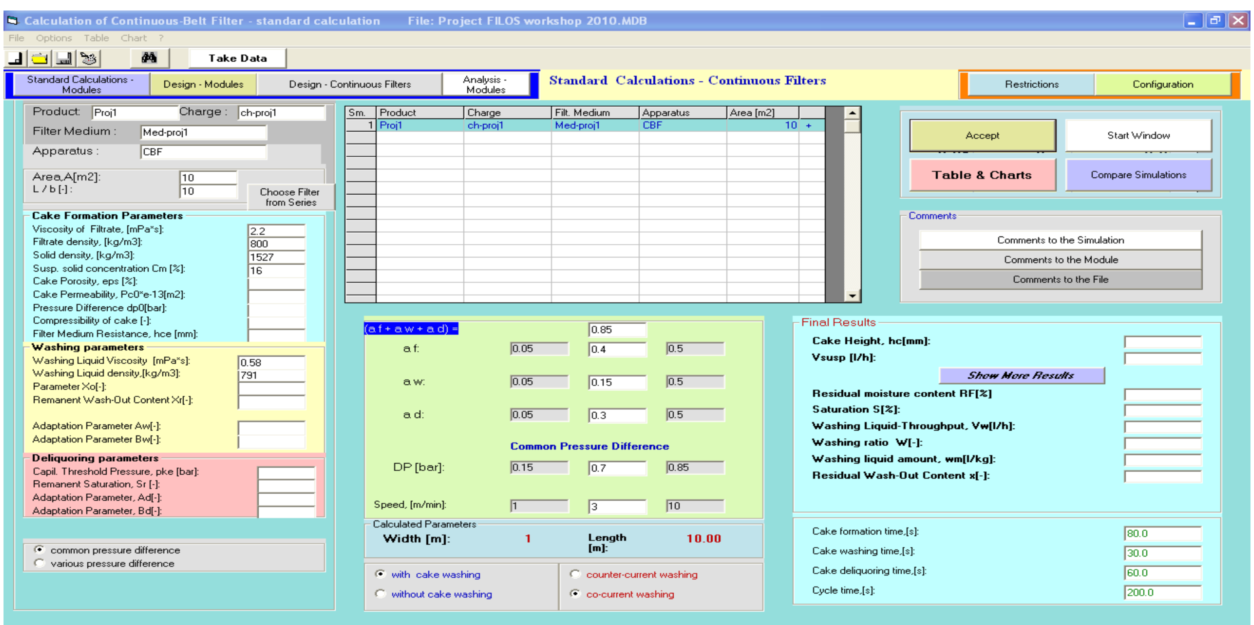


Fig. 2: As first step we enter the known material and filter parameters in the window for the Simulation of the Continuous Belt Filters (Option: *Standard Calculation*). It can be seen that we have no simulation results because the following material parameters are not yet known:

What material parameters we still need in order to have simulation results?

Cake formation parameters:

-Cake porosity (%)
-cake permeability pc0 (10^{-13} m^2) for the pressure difference dp0
-compressibility of the cake (-)
-filter medium resistance hce (mm)

Washing parameters

-Parameter X_0 (-): wash out content in the cake when the cake is saturated with mother liquid (directly after finishing the cake formation= maximal wash out content)
-remanent wash out content Xr (-): not removable content of the substance which has to be washed out
-Aw (-): adaptation parameter necessary to calculate the wash out content of the discharged cake
-Bw (-):adaptation parameter necessary to calculate the wash out content of the discharged cake

Deliquoring parameters

-pke (bar)	capillary threshold pressure
-Sr (-)	remanent cake saturation
-Ad (-), Bd(-)	adaptation parameters necessary to calculate the moisture content of the discharged cake
T (°C)	Gas temperature, necessary to calculate the gas flow rate through the cake during the cake deliquoring
α, β, γ (-)	adaptation parameters necessary to calculate the gas flow rate (necessary for dimensioning the vacuum pump)

Please notice that the calculation of the gas flow rate is optional. If in the *Configurations* window the option *Do not show Gas-Throughput* is selected then the parameters T, α, β, γ are not needed and are not displayed.

How do we get the above mentioned missing parameters?

We get the above displayed missing parameters by analyzing with FILOS the results of one test series of laboratory experiments which can be carried out by using a vacuum or a pressure device like a vacuum or a pressure nutsche. If a vacuum apparatus is used we have normally one measurement for each experiment and a test series with 9 experiments (combination of 3 pressure differences and 3 cake heights) is recommended. If a pressure nutsche with record of a filtrate mass with time is used, then 3 experiments with 3 different pressure differences are enough. If the cake is not compressible or/and if it is not necessary to calculate the filter performance for different pressures, instead of 3 pressure differences only one pressure difference equal or near to the expected pressure difference in the industrial scale is enough. And if the determination of the filter medium resistance is not necessary (that is the case when we know that it is negligible or when we don't want to determine both: cake permeability and medium resistance separately but the cake permeability of the system cake-filter medium) then even one good experiment would be enough to get just the permeability of the system cake-filter medium. The same experiment can be used to test not only the cake formation behavior but also the test the deliquoring and eventually the cake washing step.

What has to be done if for example data of only one experiment are existing and in some cases only the cake formation is tested or if no reliable test results regarding the cake washing and cake deliquoring step are existing? In such a case from this one experiment we can determine the cake porosity and the permeability of the system cake-filter medium and for the washing and deliquoring parameters we can use default values. And as it is explained below, this project is such an example, because from the 2 experiments with a vacuum nutsche only the one can be used for the analysis (exp. Nr. 2). <u>It has to be emphasized that for the cake porosity and the cake permeability no default values can be given. In any case these parameters have to be determined from tests in the laboratory scale or have to be adjusted from data of the production plant.</u>

Which are the default values for the cake washing and cake deliquoring parameters?

Default parameters for cake washing:

X_0=100	If for example we calculate a wash out content of the discharge cake X=1.2 with X_0=100 means that 1.2% of the wash out substance remain in the discharged cake.
X_r=0	we assume that for infinite wash liquid consumption the whole wash out substance can be removed from the cake (zero remanent wash outcontent in the cake)
(Aw, Bw)= (5,1)	Best case. For the standard case I recommend to keep Aw=5 and set for Bw=0.5

Default parameters for cake deliquoring:

p_{ke} (bar) Depends on the permeability value p_{c0} and on the liquid in the cake. Please use the following table as orientation for water as liquid (20 °C). If the liquid is not water then I recommend the following equation:

$$p_{ke} = \frac{\sigma}{\sigma_{water(20^\circ C)}} p_{ke_{water(20^\circ C)}}$$ with σ the surface tension

$p_{c0}/10^{-13}\,m^2$	5-10	1-5	0.1-1	0.01-0.1
p_{ke}/bar (water 20°C)	0.01-0.001	0.1-0.01	0.5-0.1	1-0.5

Sr = 0.1 – 0.2	Sr=0.1 (best case) and Sr=0.2 worst case. Please notice that these values are valid for a cake with solids without an inner porosity (no porous particles)
(Ad, Bd)= (5, 0.7)	Best case. For the worst case I recommend to keep Ad=5 and set 0.2<Bd<0.3
T (°C)	equal the temperature of the suspension
(α, β, γ)= (1, 0, 0.2)	In case of cake cracking then $\alpha>1$

<u>How do we get the parameters cake permeability pc0, cake compressibility nc and medium resistance hce?</u>

By considering the following test results (see table 1) it can be said that not enough data are existing to determine the filter medium resistance Rm as absolute value and hce as specific medium resistance (hce is the filter medium resistance related to the cake resistance rc: hce=Rm/rc with rc=1/pc). For each pressure difference at least 3 tests with different cake heights should be carried out!

Regarding the determination of the cake compressibility at least 3 experiments with different pressure difference are needed. Theoretically 2 would be enough but practically 3 are recommended. For example Dp=0.2 bar/ Dp=0.4 bar/Dp=0.8 bar (vacuum nutsche). We should try to keep the ratio Dp2/Dp1= Dp3/Dp2=const. Having in our example only 2 experiments with different pressure differences we could theoretically determine the compressibility but as it is explained below the first experiment can not be used. Knowing that in the industrial application the pressure difference was almost the same as the pressure difference of the second experiment, the cake compressibility value of nc=0 can be used. That means we should use the measured data in Table 1 to determine the cake porosity and the cake permeability of the system cake-medium.

Table 1: Laboratory filtration test results

Exp. Nr.	**Δp/bar**	**Vsus/l**	**hc/mm**	**tf/s**	**td/s**	**Ms/g**	**Rf/%**
1	0.28	2.354	28	200	60	326.2	56.8
2	0.65	2.158	20	55	60	299	13.3

For the analysis of the measured data we should use the analysis module *Single Tests* because we have for each cake formation experiment only one measurement. This module should be always used when we have cake formation experiments with a vacuum nutsche (measurement from one experiment the cake height and the corresponding cake formation time)

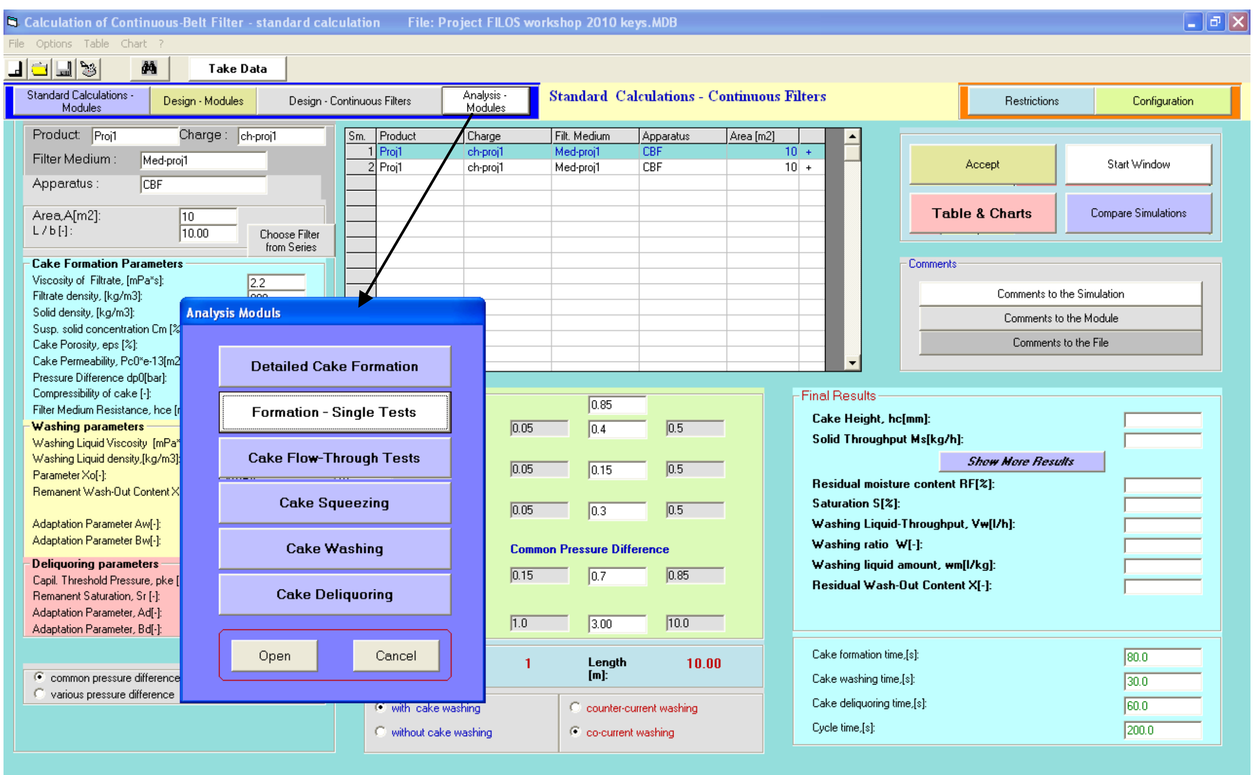


Fig. 3: First of all we go to the *Single Tests* module to enter the cake formation experiments by clicking the button *Analysis Modules* and then double clicking the *Formation-Single Tests* button or clicking the *Open* button.

Please notice that working with one FILOS-module you can go directly to any other program module (=window) by clicking the buttons *Standard Calculations Modules*, *Design Modules*, *Analysis Modules* (if you are in the *Filter Calculation* modules) or *Filter Calculation* and *Filtration Data Analysis* command buttons (if you are in the Analysis Modules).

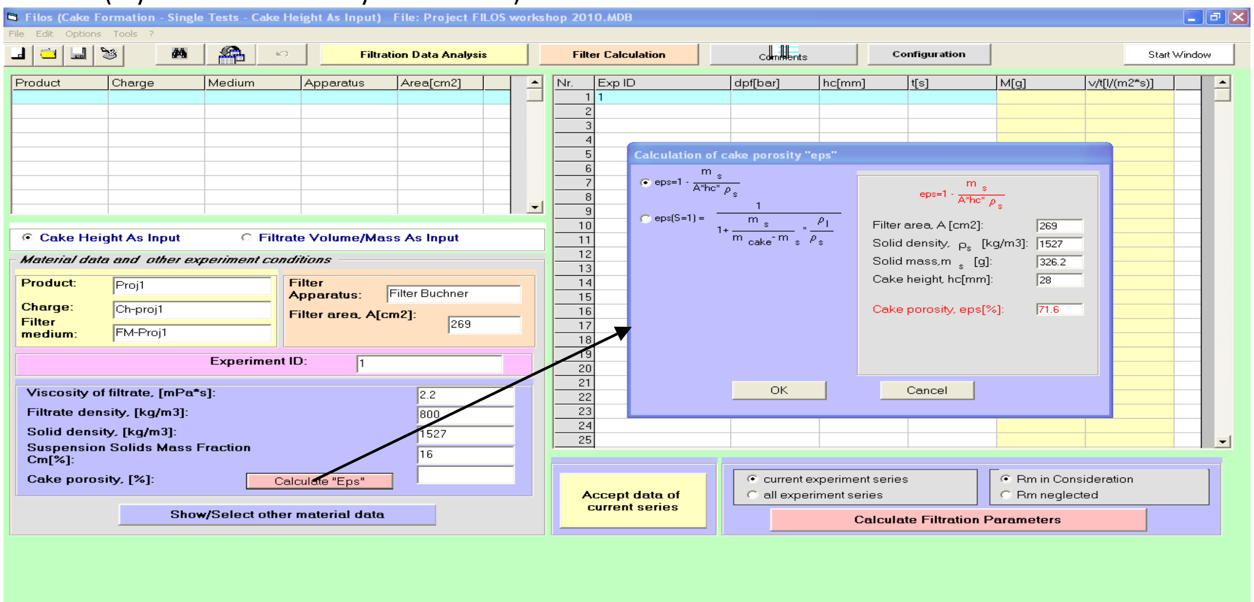


Fig. 4: As first we have to determine the cake porosity for each of the 2 tests because this parameter is needed for the determination of the cake permeability and also for the calculation of other parameters in the filter simulation module (for example the solids throughput from the cake height, the cake moisture content, the wash liquid consumption from the washing ratio etc).

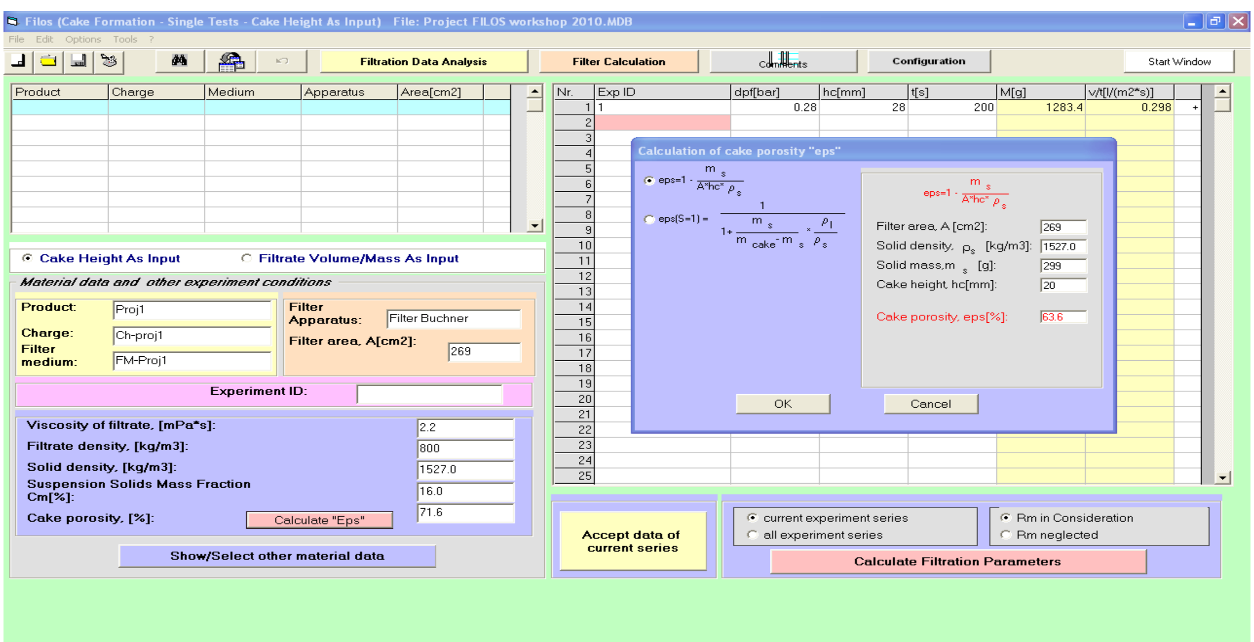


Fig. 5: The cake porosity is calculated from the filter area A, the solids density, the cake height and the dry solids mass of the filter cake.

From the given data in table 1 we have for the two experiments:

- Cake porosity (Dp=0.28 bar)= 71.6%
- Cake porosity (Dp=0.65 bar)= 63.6%

The big difference in the cake porosity between the 2 experiments can be explained by the different cake structures due to the not negligible classification effect for the experiment with the low pressure difference (this classification is caused due to the long filtration time). This high porosity value and the classification effects can be verified from the high measured cake moisture content (Rf=56.8%). This Rf-value corresponds to the measured cake porosity and to a saturated cake (S=100%). Due to the relatively high cake permeability of the low-pressure experiment (pc=3.3) according to the given default values we should expect a capillary threshold pressure of less than 0.1 bar. But not having any cake deliquoring for this experiment means that in this case we had pke>0.28 (Dp=0.28 was the pressure for this experiment).

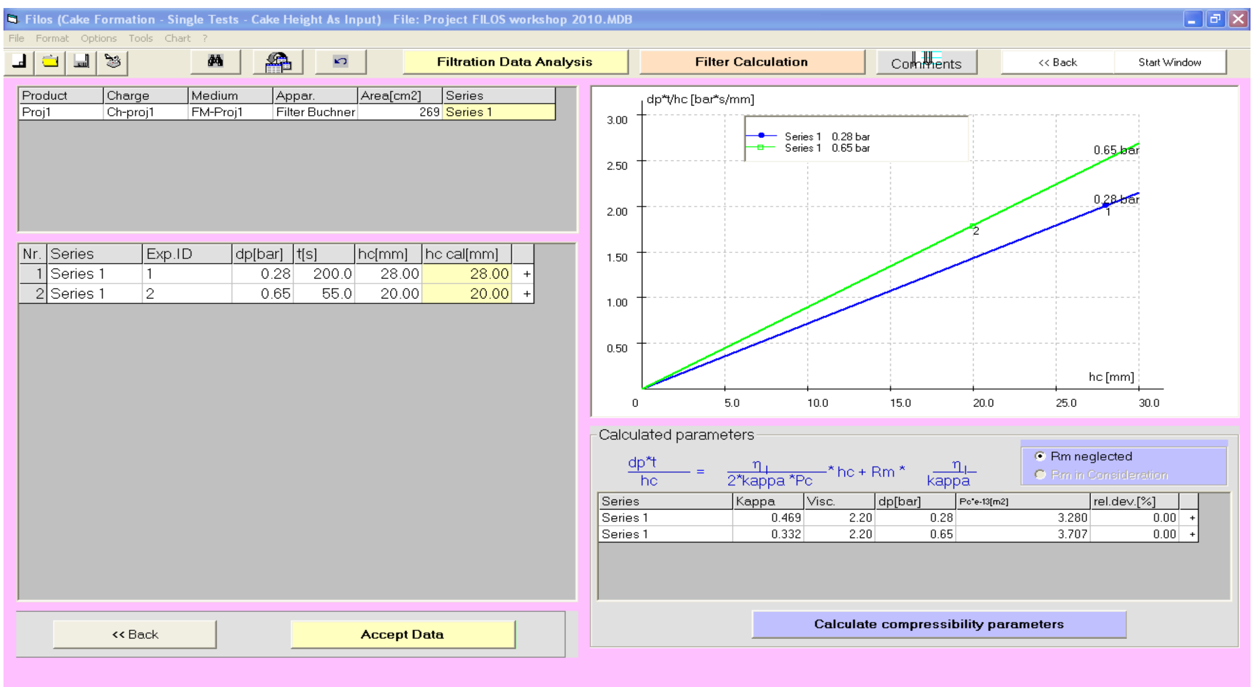


Fig. 6: As can be seen in the results window of the Single-tests module the experiment with the lower pressure difference has smaller permeability than that with the higher pressure difference and although it has a higher cake porosity (cakes with the same particle size distribution which form a homogenous cake it are expected to have a higher cake permeability if the cake porosity is higher). This result means that the cake was formed not homogeneously: due to classification we have in the upper part of the cake fine particles with a relatively higher porosity than the cake regions near the cake.

From the above explanations (see text for figure 6) we should use for the Belt filter calculation the cake permeability of the second experiment (Dp=0.65 bar). Why?

-The test with Dp=0.65 bar is very close to the recommended operation pressure difference of the industrial filter.

-This test is more reliable (sedimentation effects for the small pressure leads to fine particles on the surface with less cake permeability, see explanation above)

Analysis of the cake deliquoring tests

The cake deliquoring test results (measurement of cake moisture content and eventually of the gas flow rate for definite cake height, pressure difference and deliquoring time) can be analyzed with the FILOS-Analysis module *Cake Deliquoring*. The analysis of the measured cake moisture content Rf can be done even with one good experiment (normally we should do 3 experiments).

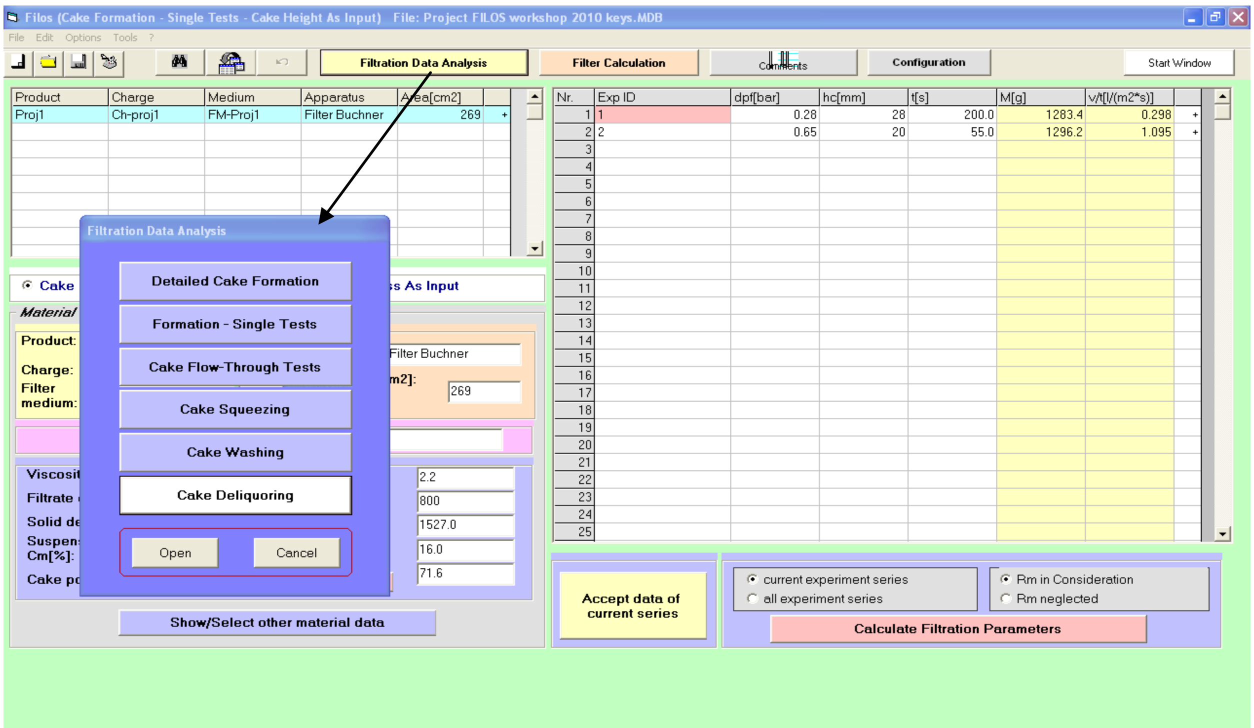
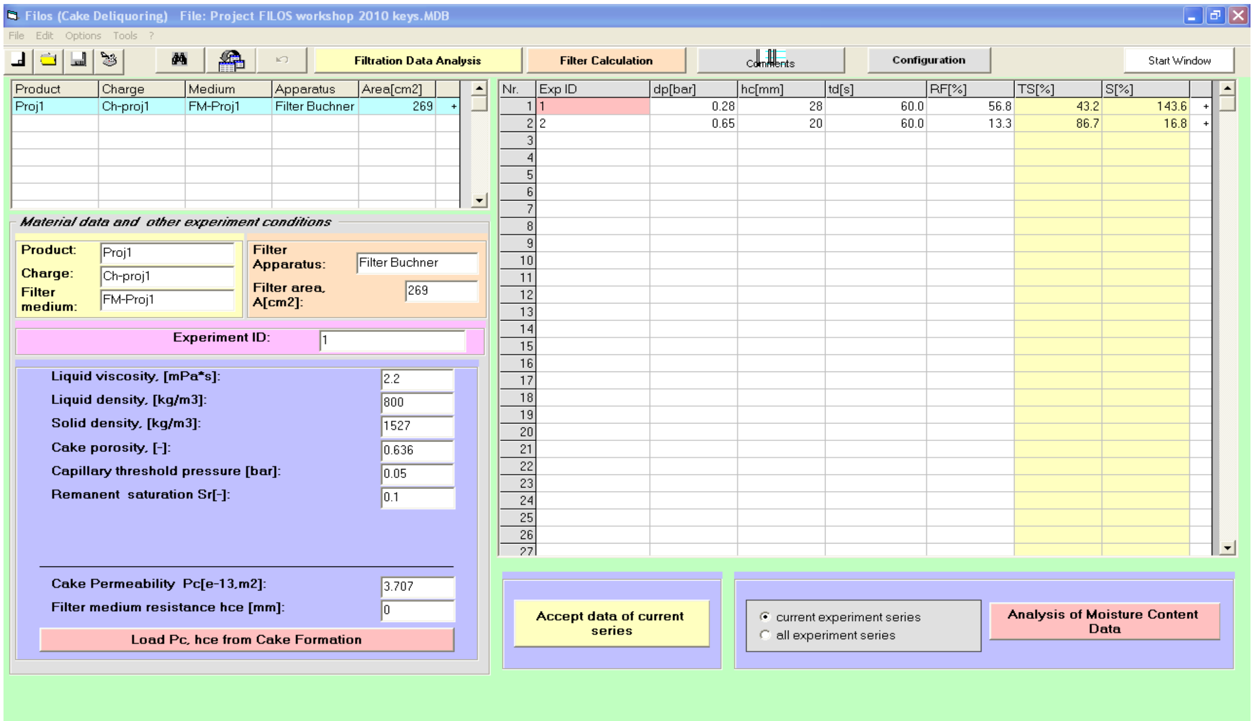


Fig. 7: We go to the data-input window (main window) of the *Cake Deliquoring* module by clicking the button *Filtration Data Analysis* and Double clicking the button *Cake Deliquoring* or clicking the *Open* –button

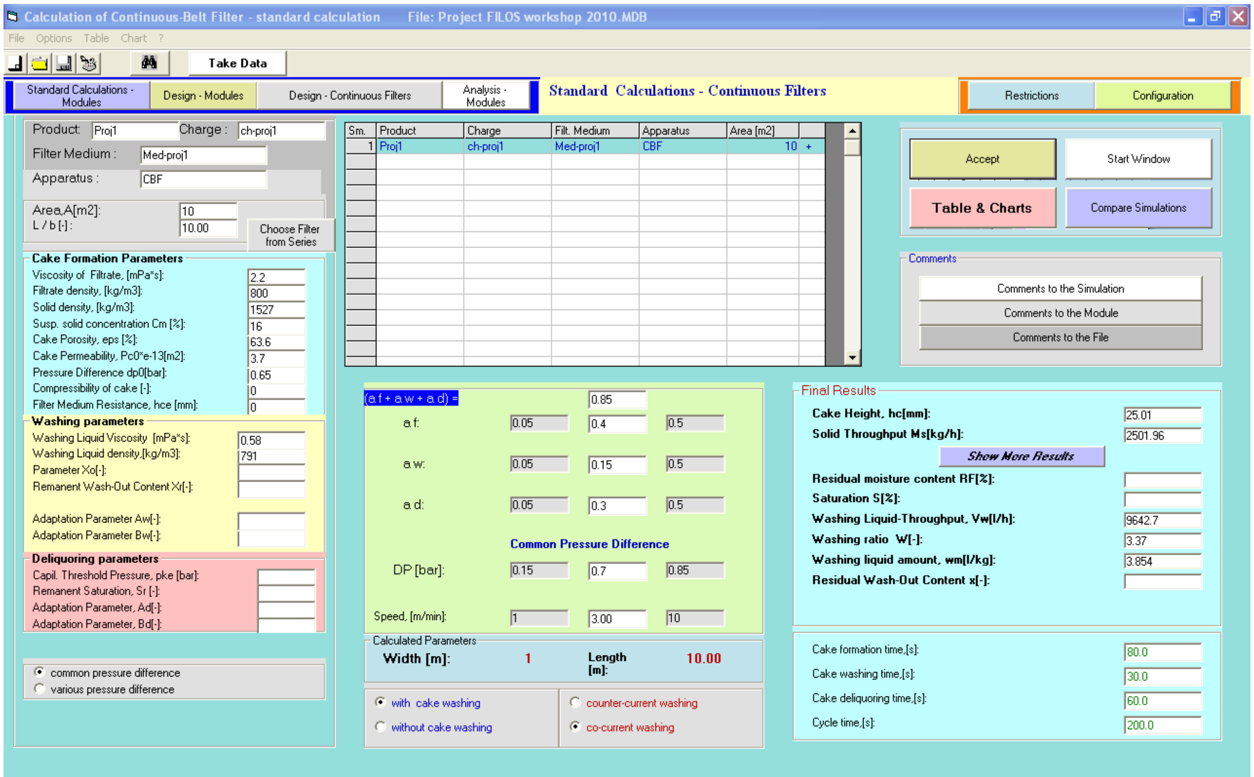
In the data input table (see right part of the screenshot in fig. 8) we see the test results of the 2 experiments. Each row corresponds to one measurement. We enter first a test name, then the pressure difference during the deliquoring step (dp), the cake height (hc), the deliquoring time (td) and the measured cake moisture content RF. The last 2 columns in yellow color display the calculated cake solids content TS (TS=1-RF) and the cake Saturation S (Definition: S is the liquid volume in the cake related to the cake voids volume, that means we should always have S<=100%). As can be seen, the cake saturation of the first experiment is even higher than 100%. This is due to the fact that in this module for the experiments of one Test Series an average porosity for all experiments of this series is used. Knowing that the porosity of the first experiment is 71.6% and not 63.6% (the porosity of the "good" experiment=63.6% was used in this module) we can explain the Saturation value of higher than 100%. Using the cake porosity of 71.6% we get for the first experiment S=99.5% as an evidence that we can not use this test for the regression analysis. Since we need 2 adaptation parameters, one measurement is not enough to deliver us with the parameters Ad and Bd (please notice that in the new update of the program that will delivered soon (FILOS 2011) even with one deliquoring experiment we can get the adaptation parameters Ad and Bd).



<u>Fig. 8:</u> Coming to the main window of the *Cake Deliquoring* module (see above) we see that the values of the parameters which are common with the cake formation step (including the series description parameters) are taken automatically. Only the deliquoring specific parameters: capillary threshold pressure pke and remanent saturation Sr have to be entered. As described before (page 6) we can enter default values for these parameters and it is not necessary that we measure them. Any deviations from the real values are "corrected" by the adaptation parameters Ad and Bd. The cake permeability pc and the filter medium resistance hce can be taken from the cake formation step by clicking the command button *Load Pc, hce from Cake Formation*.

We go now to the Belt Filter Calculation and we enter the following data (see fig. 9):

Cake porosity Eps= 63.6%
Pc0= 3.7
Dp0=0.65 bar
Cake compressibility =0
Filter medium resistance hce=0



<u>Fig. 9:</u> No washing and no deliquoring performance parameters can be calculated because the cake washing and deliquoring material parameters are still missing.

What about the washing parameters? No washing tests were done and that's why we assume default values: X_0=100, X_r=0, Aw=5, Bw=0.7 (these Aw, Bw combination ensures a good washing efficiency)

What about now the cake deliquoring parameters Ad, Bd? As we saw, the Analysis module *Cake Deliquoring* needs at least 2 good measurements for the determination of Ad, Bd. In such a case when we have only one measurement we use the so called "practical way" to determine the Bd-value (the Bd is the key adaptation parameter for describing the deliquoring kinetics!). The practical way works as follows: We use the FILOS-nutsche module to simulate the one good deliquoring experiment (see fig. 10).

(please notice that with the new update of the program that will delivered soon (FILOS 2011) even with one deliquoring experiment the adaptation parameters Ad and Bd can be determined.

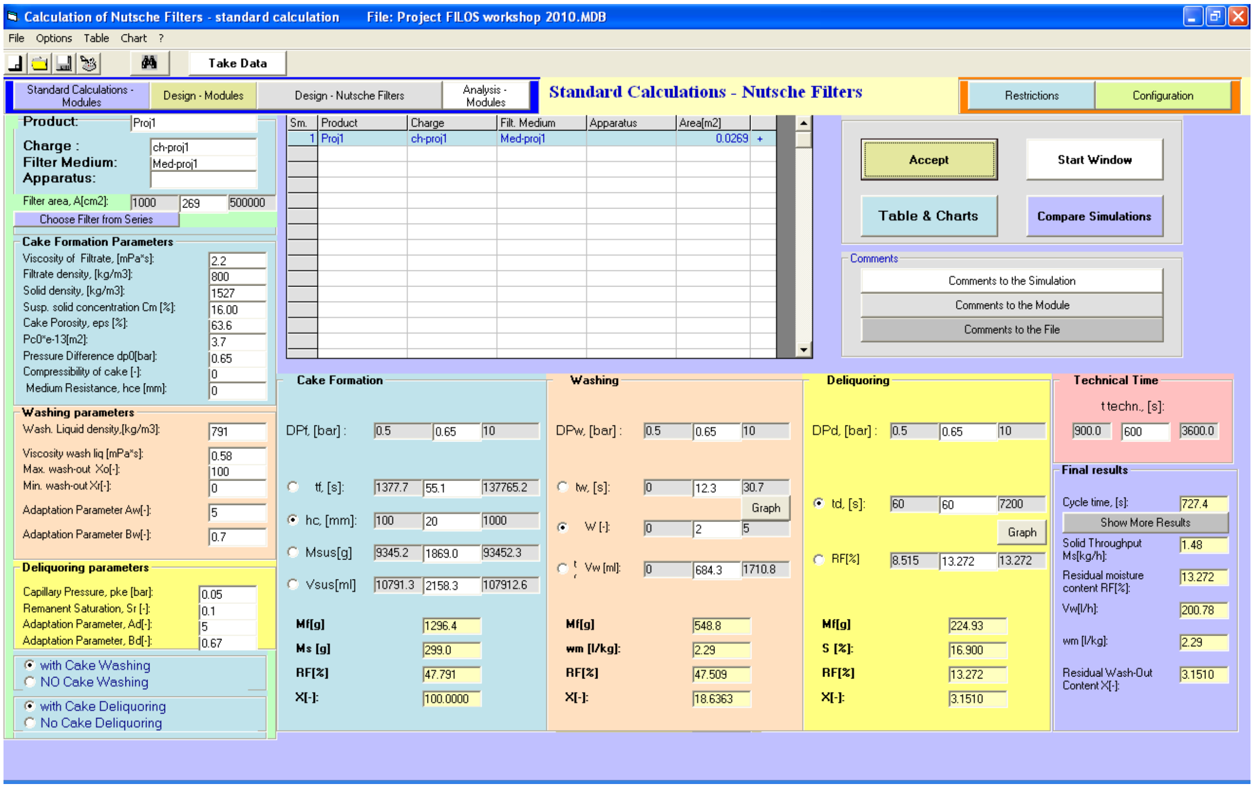


Fig. 10: This is the simulation of the laboratory experiment with the cake height of 20 mm and a pressure difference of Dp=0.65 bar. For getting the deliquoring parameter Bd we enter in the field Deliquoring parameters (yellow field on the left) as default: p_{ke}=0.05 bar, Sr=0.1, Ad=5 and knowing that in the experiment for a deliquoring time of 60 s we had Rf=13.3% we change Bd in such a way that we have the calculated Rf equal this measured value. The Bd we get by using this so called "practical way of determining the adaptation parameters" is Bd=0.67.

Having now determined all necessary material parameters we go again to the module *Continuous Belt Filters* (Option: *Standard Calculation*) and we enter them manually in the input fields on the left side of the window (see fig. 11). Please notice that besides the manual entering of the material parameters in the *Filter Calculation* – modules we can take the determined material parameters from the Analysis modules by clicking the command button *Take Data*. The *Take Data* - tool is the interface between the FILOS-Analysis modules and the FILOS-Filter Calculation modules.

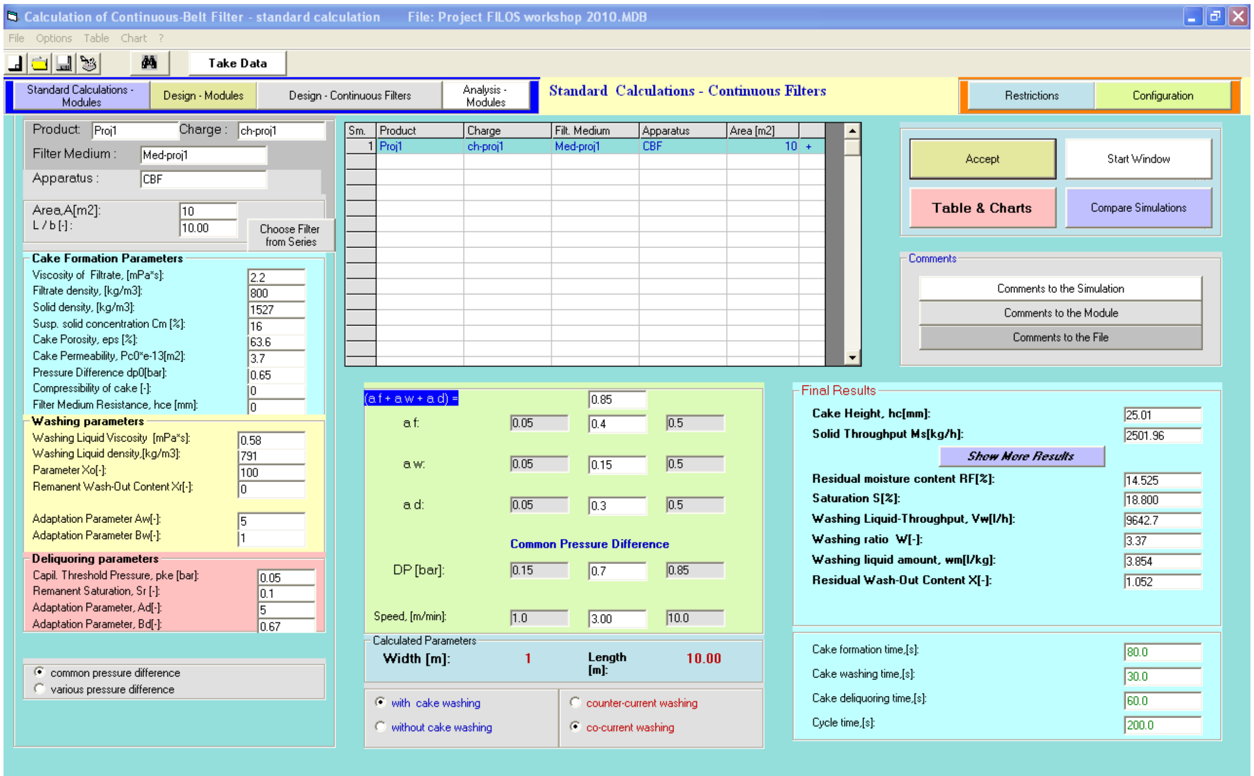


__Fig. 11:__ After entering the missing material data (compare with fig. 9) we can see that we have now calculation of all performance parameters of the Belt filter. Comparing the required performance with the results we get (see field *final results* on the right of the above screenshot) we see that the required cake moisture content of Rf<12% can not be achieved. Only the solids throughput (required value 2500 kg/h) and the wash out content in the cake (required value X<1%) could be reached. The given wash liquid consumption of < 1.5 l/kg dry solids for the co current washing option is also not possible. We are expecting 3.85 l/kg dry solids (see washing liquid amount wm in the final results).

__Task 2__

Which setting parameters you should preferably change to achieve a higher solids throughput without negative effects in the cake moisture content and the washing efficiency?

The belt speed is the parameter that influences the solids throughput but not the moisture content and not the wash out content in the cake. Why? The higher the belt speed, the thinner the cake but the shorter the washing and deliquoring time, so that the advantage of a thinner cake regarding washing and deliquoring kinetics is compensated by the shorter times for the washing and the deliquoring step.

Task 3

What setting parameters you should change if you want to have significant changes in the cake moisture content?

To change significantly the cake moisture content we should change the ratio of the specific areas for cake deliquoring to cake formation: ad/af. The higher ad/af is, the lower the cake moisture content.

Task 4

Considering the possibility of a production increase (new solids throughput= 4000 kg/h) what filter size you should purchase to be able to have also this increased productivity if the cake height shouldn't be smaller than 25 mm, the moisture content and the wash liquid consumption should be the same as the original design with the lower solids throughput. What is the required area division for cake formation, washing and deliquoring if 95% of the total area can be used for these steps and which the belt speed?

To solve this problem we go to the *Filter Design* option of the *Continuous Belt Filter* module. To go to this window you can click the command button *Design Modules* and then double click the button *Continuous Belt Filters* or directly click the button *Design Continuous Filters*.

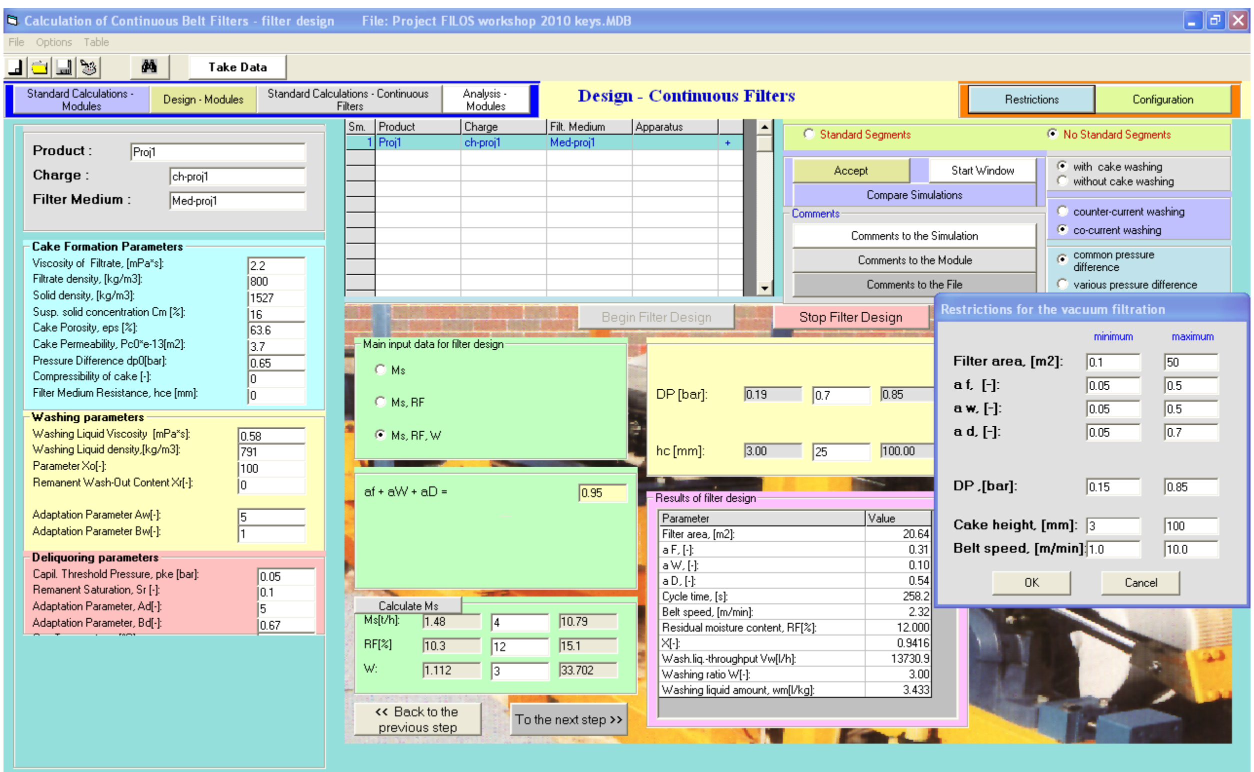


Fig. 12: The Design-results for a higher solids throughput (4 t/h=4000 kg/h) and RF=12%, W=3 (W=washing ratio, defined as wash liquid volume related to the cake voids volume)

Before clicking *Begin Filter Design* be sure that for the Restriction parameters, which influence the Filter Design, meaningful min-max values are entered. Click first the command button *Restrictions* to see the min-max values and change the ad-max to 0.7 instead of 0.5. Because we want to have relatively low cake moisture content we should allow for the maximal value of the specific deliquoring area admax as high as possible.

After having changed the admax to 0.7 (instead of admax=0.5) we close the *Restrictions*-window and we click *Begin Filter Design*. As first we select which performance parameters we want to enter (select the Option "*Ms, Rf, w*" that means we want to enter the solids throughput, the cake moisture content and the washing ratio w) then enter the wished pressure difference (Dp=0.7) and the wished cake height (25 mm) and as last the sum of the specific areas for cake formation, washing and deliquoring (af+aw+ad=0.95). After clicking *To the next step* we enter the required data to consider the production increase (Solids throughput Ms=4 t/h, RF=12%, w=3). The washing ratio w=3 enables a good washing which results in an X<1%.

The program by using the material parameters, the restriction parameters and the entered values of Dp and hc calculates for the performance parameters Ms, Rf and w the min-max values so that the user can enter only meaningful data. Finally after clicking *To the next step* we have a display of the Filter Design results (see fig. 13):

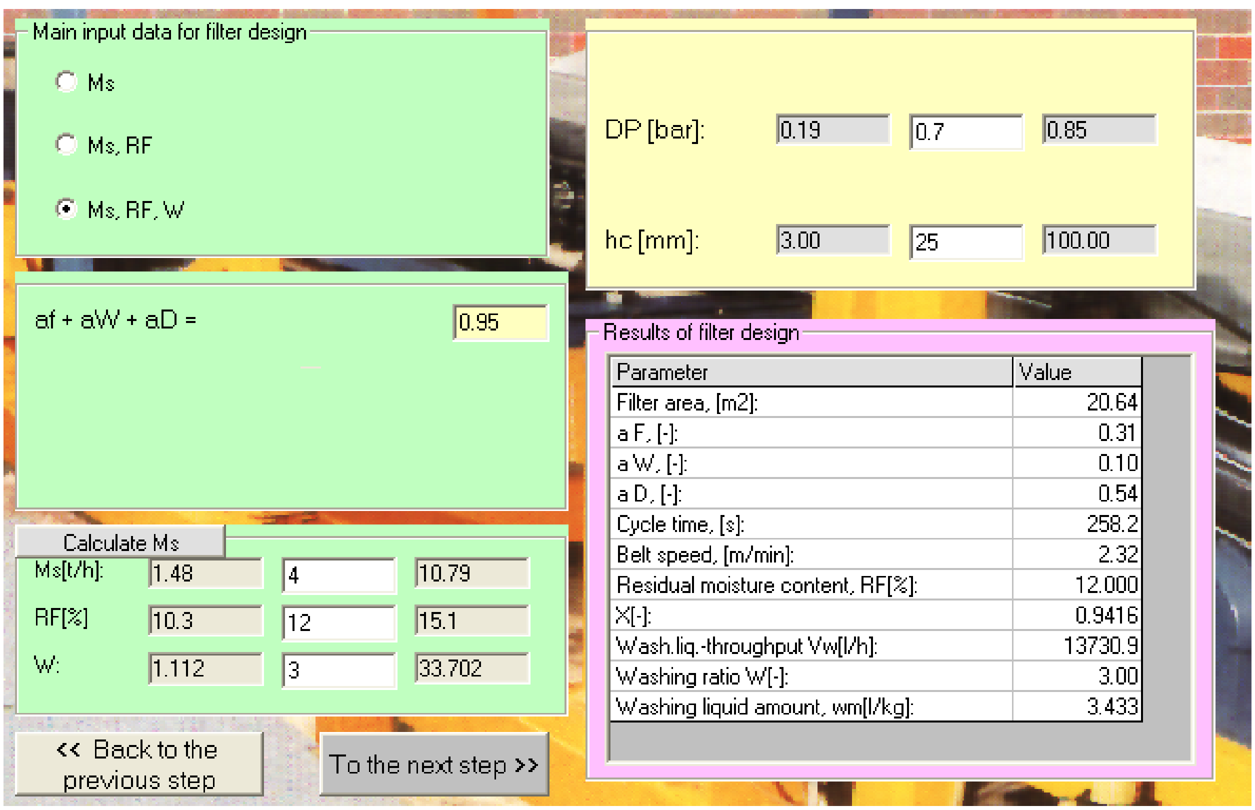


Fig. 13: We see that for the case of a higher production a filter with an area of 20.64 m^2 is needed with the following zone division for the cake formation, washing and deliquoring: af=0.31/ aw=0.1/ ad=0.54. The required Belt speed is 2.32 m/min.

Task 5

If you have decided for the bigger filter size (A=20 m^2) in order to consider the possible production increase then which settings you should have for the current requirements (solids throughput 2500 kg/h)?

After having decided for the Filter of 20 m^2, as we know, the only setting parameter which changes the solids throughput without changing the cake moisture content Rf or the cake wash out content X is the belt speed. By reducing the Belt speed to 1 m/min (instead of 2.32 m/min which gives a productivity of 4000 kg/h) we reach as can be seen in fig. 14 the requirements of the project (Solids throughput = 2500 kg/h, cake moisture content RF<12% and wash out content X<1%).

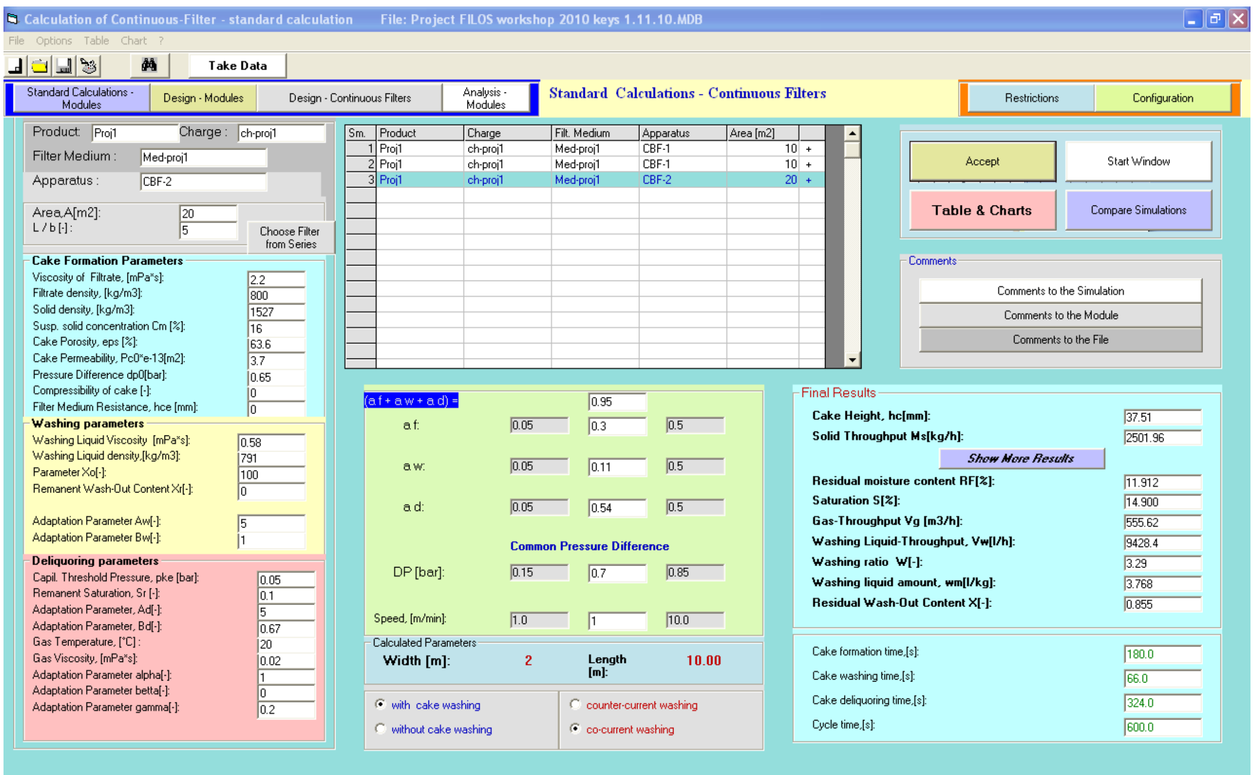


Fig. 14: Taking the Design Results for the higher solids throughput (see fig. 12) with this calculated filter geometry and filter zone division (af, aw, ad) we use the standard calculation module and we change only the belt speed until we get the current required solids throughput of 2500 kg/h.

Task 6

Is the pre thickening of the cake instead of purchasing a bigger filter size also a reasonable choice? Explain why.

Higher suspension solids concentration allows a smaller specific cake formation area and a higher belt speed. The smaller specific cake formation area *af* allows a higher specific area for cake deliquoring *ad* (that means we can have a relatively high value for ad/af, which gives us the required low moisture content RF<12%). The high belt speed compensates the small cake formation area and enables the achieving of the required higher capacity (Solids throughput: 4000 kg/h). That means the pre thickening of the suspension and the buy of the small filter (A=10 m^2) is in this case an alternative to the first option (buy a bigger filter A=20 m^2 with the original suspension solids concentration).

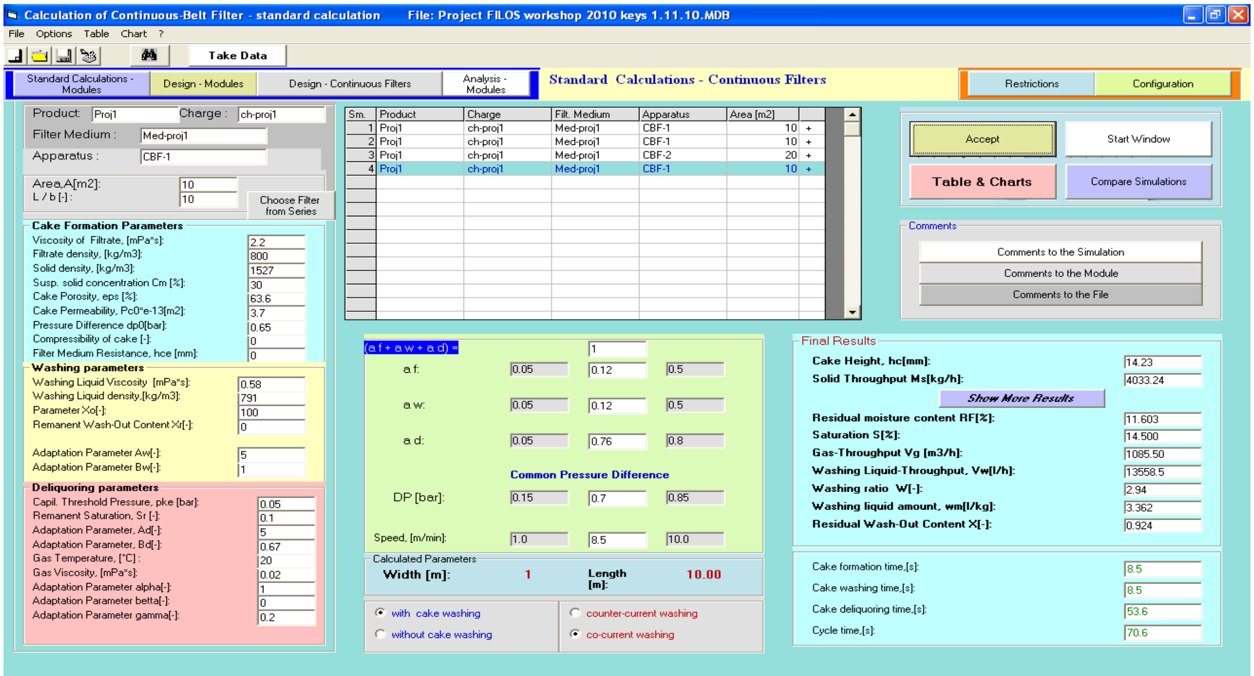


__Fig. 15:__ Calculation of the performance of a belt filter with only 10 m^2 (instead of 20 m^2) for the case of the suspension pre thickening (new suspension solids mass fraction Cm=30% instead of 16%). By changing the zone division (smaller specific area for cake formation and bigger for cake deliquoring) and increasing the belt speed we achieve the requirements for the higher solids throughput (4000 kg/h).

__Task 7__

To judge if the selected filter medium regarding filter capacity is for this application the correct one, you asked the manufacturer to give you the determined filter medium resistance. Why the manufacturer couldn't give you this value? What tests are necessary and how they should be carried out to have a reliable value of the filter medium resistance?

To have a reliable value of the filter medium resistance we need for vacuum nutsche tests (with no measurement of the filtrate mass as a function of time during the cake formation experiment) at least 3 experiments with the same pressure difference and different cake heights. The range of the measured cake heights should be relatively big (for example 10 mm, 20 mm, 40 mm). In our case we had for the good experiment (Dp=0.65 bar) only one cake height (hc=20 mm) and that's why the filter medium resistance can't be determined. That means the determined permeability of pc=3.7 * 10^{-13} m^2 is the permeability of the system cake and filter medium.

Task 8

Do you think that the determination of the cake compressibility is for this case and the given apparatus possible? Why the determination of the cake compressibility is in this case not necessary?

As we could see (comments fig. 6) we had for the small pressure difference during cake formation not negligible overlapping of sedimentation, which resulted in different cake structure for the two different pressure differences. That's why the determination of the cake compressibility is not possible. Only with higher suspension solids concentration we can neglect the classification effects and we can determine in this case the cake compressibility (but at least 3 experiments with different pressure differences and possibly with: Dp2/Dp1=Dp3/Dp2 are necessary).

For this project the determination of the cake compressibility was not necessary because we have an experiment with almost the same pressure difference (Dp=0.65 bar) as the recommended pressure difference of the industrial filter (Dp=0.7 bar).

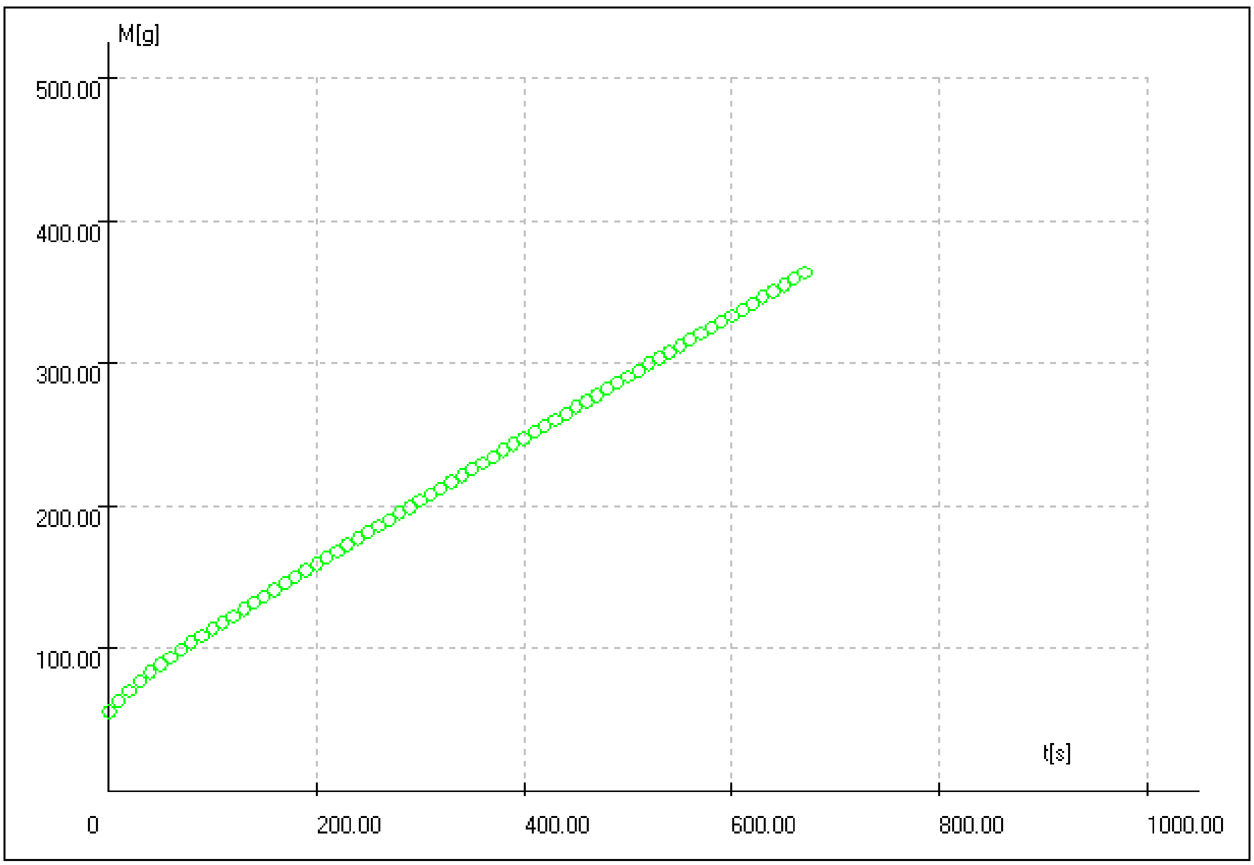
Project 2

The judgment of the filtration (=cake formation) experiments and the correct determination of the filtration parameters (cake permeability pc0, cake compressibility nc and filter medium resistance as absolute (Rm) and specific (hce) value) by using FILOS

Project 2.1

Judgment and correction of the filtration curves

You have used a laboratory pressure nutsche to determine the filtration behavior of a diluted suspension for an oil- clarification project in the food industry. You carried out one filtration experiment with a pressure difference of 0.5 bar and during the test you registered the filtration mass as a function of the time. The data are given as an excel table (see Excel file sheet Proj2.1). The filtration curve is the following:



Tasks

1. Why do you think that this curve doesn't belong to the typical form of the filtration curve M=f(t)?
2. Use FILOS to judge first the experiment by diagnosing "real effects" which contribute to the deviation of the filtration curve from the ideal case (=theoretical expected). That means we

want to answer the question: What happened during this experiment just by analyzing the $M_f(t)$-data by using FILOS

For the data analysis with FILOS use the following suspension parameters:

Viscosity of filtrate, [mPa*s]:	1
Filtrate density, [kg/m3]:	1000
Suspension density, [kg/m3]:	1030.0
Solids Concentration C[g/l]	57.00
Concentration parameter, kappa[-]: Calculate "kappa"	0.038

3. Can we get reliable filtration parameters (cake permeability and filter medium resistance) even from such curves which show big deviations from the expected form? If yes, determine the cake permeability and the filter medium resistance from these data.

Task 1:

Why do you think that this curve doesn't belong to the typical form of the filtration curve M=f(t)?

a) For the time t=0 we should have filtrate mass M=0 but we have here for t=0, M>0. This happens especially for suspensions with very low solids concentration where we have a flow of suspension through the medium before applying the pressure difference (that means before starting the experiment).

b) After some filtration time the curve M=f(t) is linear. That is an evidence that the cake is already formed and above the cake we have only filtrate which flows through the already formed cake of a constant cake height.

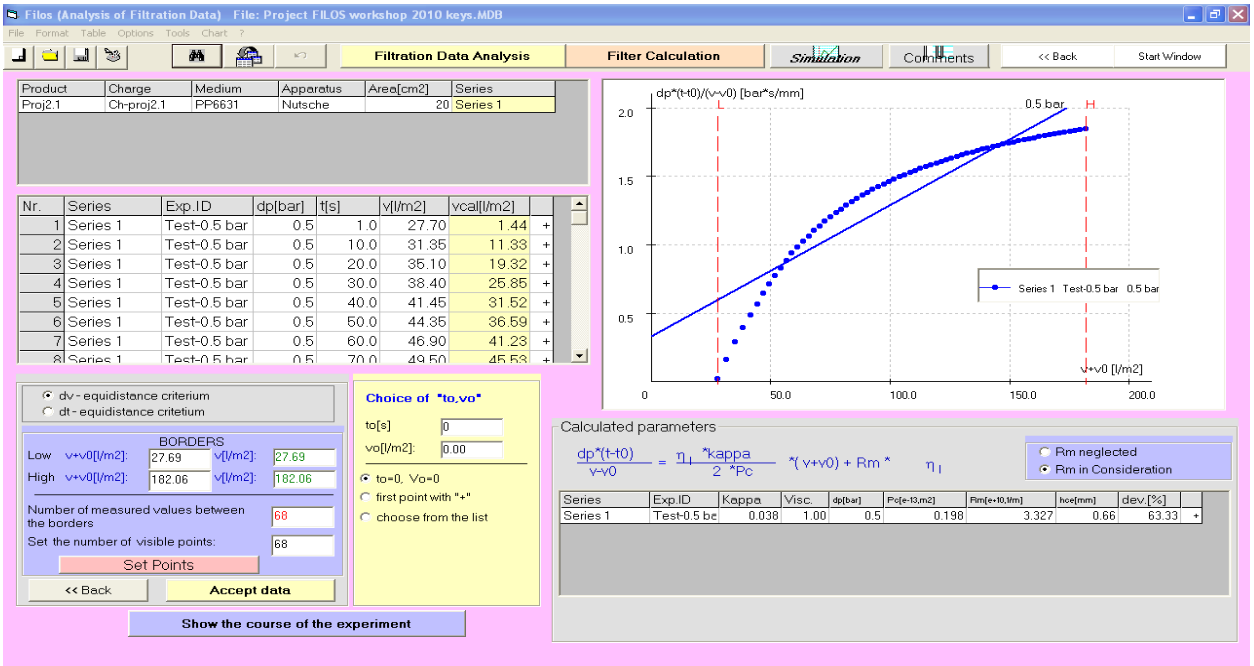
Task 2:

Use FILOS first to judge the experiment by diagnosing "real effects" which contribute to the deviation of the filtration curve from the ideal case (=theoretical expected). That means we want to answer the question: What happened during this experiment just by analyzing the $M_f(t)$-data by using FILOS.

For the analysis of the given filtration experiment the following data are needed:

Viscosity of filtrate, [mPa*s]:	1
Filtrate density, [kg/m3]:	1000
Suspension density, [kg/m3]:	1030.0
Solids Concentration C[g/l]	57.00
Concentration parameter, kappa[-]: Calculate "kappa"	0.038

As can be seen in fig. 16 (results window of the FILOS-module Detailed Cake Formation) the linear regression analysis gives us a bad fitting of the measured points. We need to correct the last measurement points (sedimentation effect) and the errors at the beginning of the experiment due to the break-through of suspension before starting the experiment.



<u>Fig. 16:</u> Results window of the FILOS-module *Detailed Cake Formation* with a theory based diagram that enables the correction of the filtration measurements

FILOS enables also the analysis of the filtration data by using the differential cake formation equation (see fig. 17). This analysis option enables the correction of the data. Using this option is for example easier to detect and eliminate from the regression analysis all points which belong to the time interval at which we have more a “flow-though” experiment than a cake formation experiment. That is the interval at which almost only filtrate is above the cake because all particles are already sedimented.

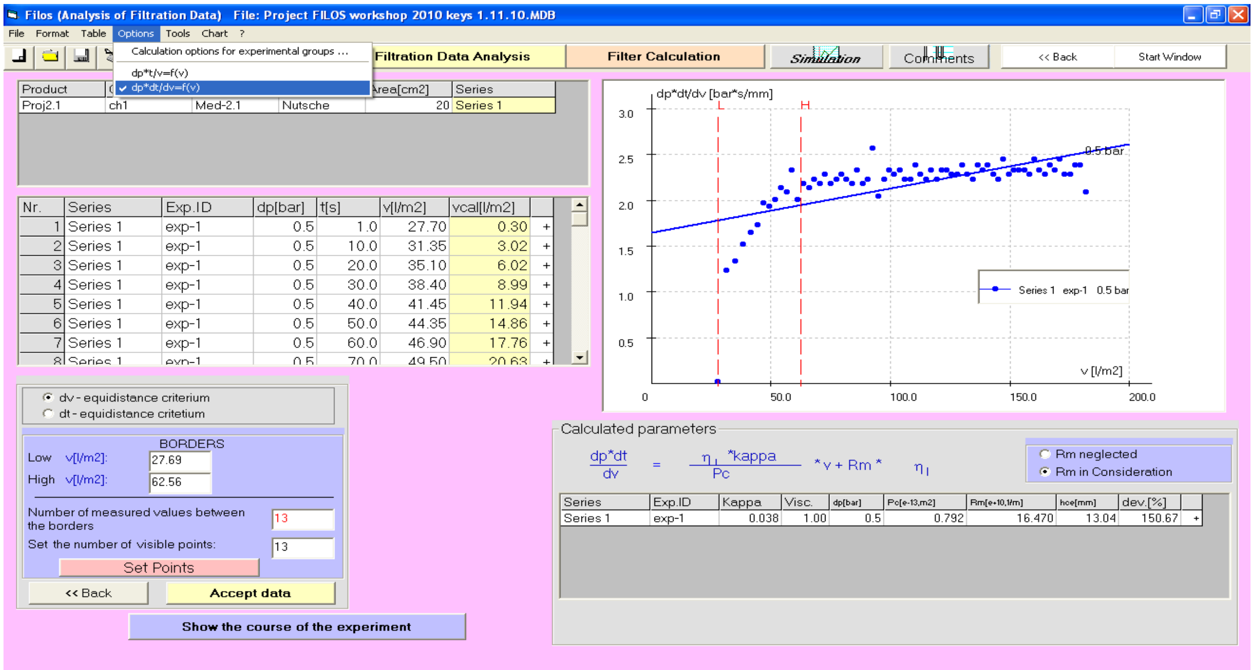


Fig. 17: Differential method for the analysis of the filtration experiment. This method is very useful for the correction of the filtration experiments.

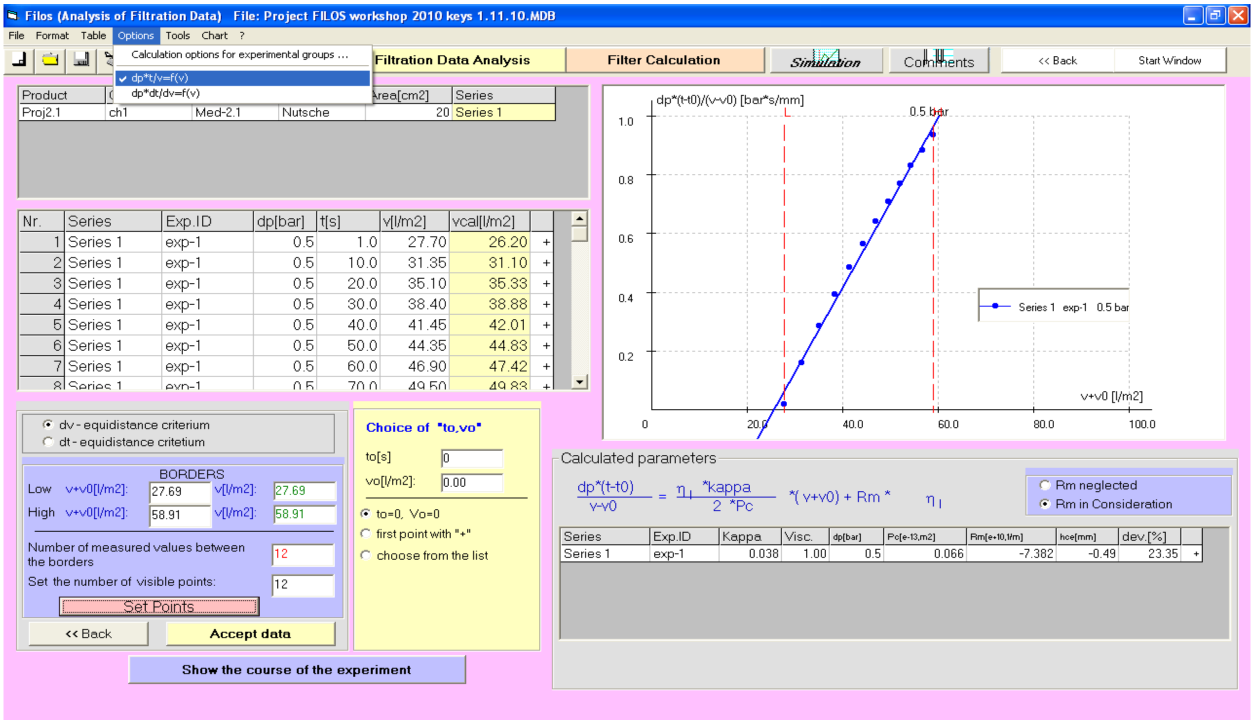


Fig. 18: the integral method with t0=0 in many cases can't deliver us the correct values of the filtration parameters because the errors which we have due to wrong measurements at the beginning of the experiment can't be eliminated although we remove these first measurements!

For the correction of the wrong measurements due to classification (see fig. 17): We move the right red vertical line to such a point (see above) so that on the right of this red line we will have all measured points which should be excluded from the regression analysis and then we click the command button *Set Points*. Then we select the integral cake formation equation with the option t0=0 (see fig. 18). As can be seen we have still an error due to the break-through of suspension before starting the experiment (=before applying the pressure difference). As last correction step we select the general integral cake formation – equation (t0>0) by selecting the option *first point with "+".* This option enables the correction of the errors at the beginning of the cake formation experiment. In fig. 19 you see the corrected curve, which gives correct values for the cake permeability and the filter medium resistance.

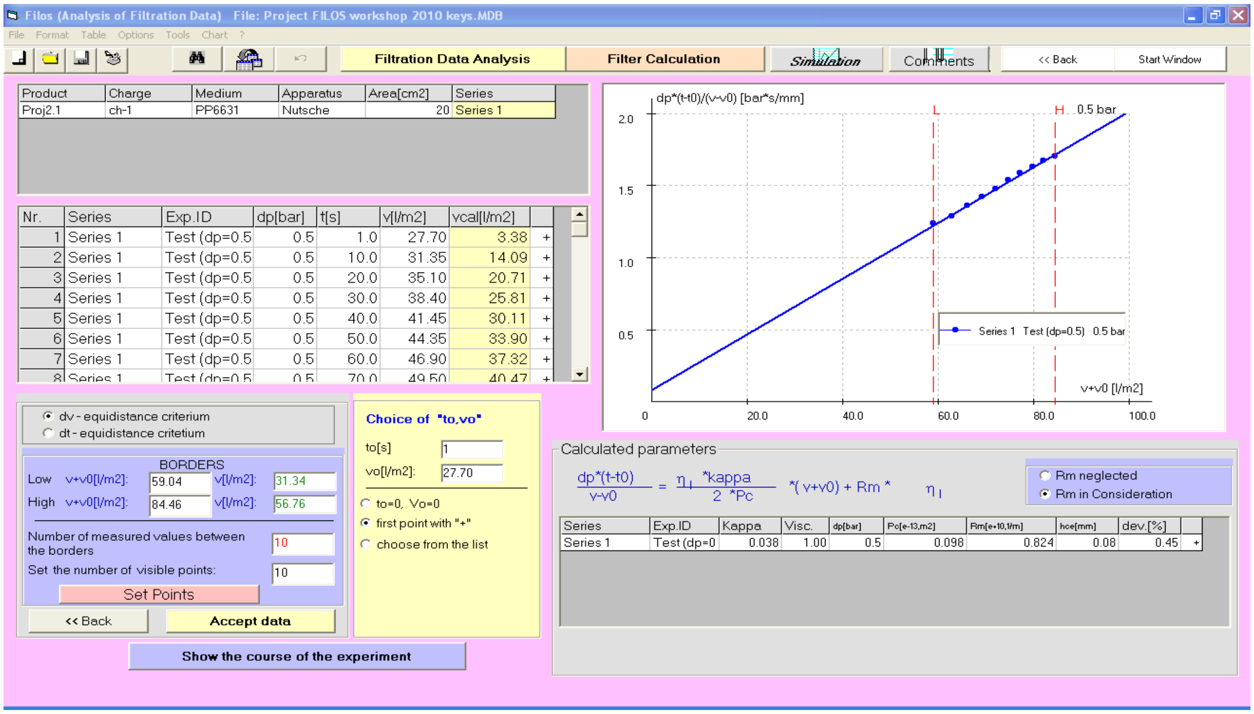


Fig. 19: The general integral analysis method of the filtration experiment (option: first point with "+") enables the correct determination of the filtration parameters: cake permeability pc and filter medium resistance Rm and hce (hce= specific filter medium resistance with hce=pc *Rm)

Task 3

Can we get reliable filtration parameters (cake permeability and filter medium resistance) even from such curves which show big deviations from the expected theoretical (=ideal) form? If yes, determine the cake permeability and the filter medium resistance from these data.

The answer is YES. As described above (see Task 2) FILOS enables first the correction of the cake formation curve and then doing regression analysis by using the corrected data and the general integral method (option: *first point with "+"*)we get correct values for the cake permeability and the filter medium resistance (see fig. 19) For the Project 2.1 we get Pc=0.098 $*10^{-13}$ m^2 and Rm=0.824 $* 10^{+10}$ m^{-1}. However the determined permeability is due to not constant suspension solids concentration during the cake formation smaller than the expected permeability when we have cake formation with constant suspension solids concentration.

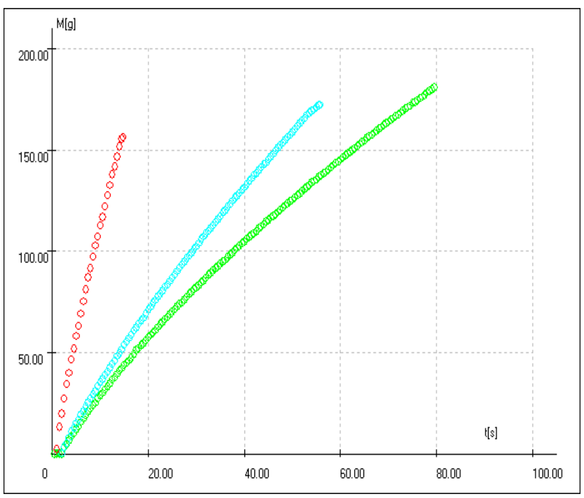
Project 2.2

The correct determination of the filtration parameters as necessity for the proper filter selection and the correct filter design and optimization

The exact determination of the cake permeability, the cake compressibility and the filter medium resistance should be a priority task for everyone who is dealing with filtration, because especially the cake permeability and the cake compressibility are key- parameters for the selection of the proper filtration equipment and the optimization of its performance. But even for those who just want to characterize the suspension, are cake formation tests for obtaining the cake permeability of importance (for example judge the influence of different crystallization conditions by filtering the suspension and determining the cake permeability).

Given are two suspensions, which are tested systematically with a laboratory pressure nutsche (for each suspension 3 experiments with variation of the pressure difference are carried out).

Tasks:



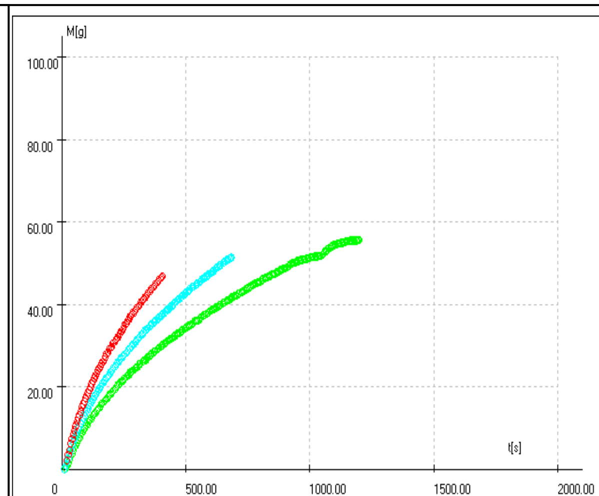


Diagram left: Susp Proj2.2-1 (green curve: Dp=0.6 bar/ blue curve: Dp=1 bar/ red curve: Dp=4 bar)
Diagram right: Susp Proj2.2-2 (green curve: Dp=1 bar/ blue curve: Dp=2 bar/ red curve: Dp=4 bar)

Tasks:

1) From the measured curves above try to compare qualitatively the filterability of the suspensions and eventually detect errors and real effects which contribute to deviations from the ideal cake formation curve.

2) Compare 3 different methods for determining the cake permeability and the filter medium resistance by using FILOS and taking as example the first experiment of the Susp Proj2.2-1 (Dp=0.6 bar). The methods are the following: Integral method (Dp t/v =f(v)), general integral method (Dp (t-t0)/(v-v0) =f(v+v0)) and the differential method (Dp dt/dv=f(v)). What conclusions can be deduced?

3) Determine for both Suspensions the cake permeability pc0, the cake compressibility nc and the filter medium resistance by using the measured filtrate mass as a function of time (see excel file sheets "Susp X1" and "Susp X2") and the data given in the table below

Suspension Name	Viscosity mother liquid/ mili Pas	Density mother Liquid/ kgm-3	Density solids/ kgm-3	Suspension Solids mass fraction/%	Cake porosity/%
Susp Proj2.2-1	1	1000	2700	32.3	46
Susp Proj2.2-2	1	1000	2500	30	65

4) What values of the filtration parameters we get in case that we do not do any corrections of the measured data and what is the reason of the errors of the measured data for these two test series?
5) Why it is better to include in the y-axis parameter of the theory based diagram the pressure difference Dp? How we can recognize the cake compressibility from the curves of one test series in the theory based diagram?
6) What can be said about the filter media, which were selected for both suspensions? How the absolute filter medium resistance depends on the pressure difference Dp?
7) The reason why you did this analysis was mainly to find out if the suggestions of the filter manufacturers regarding the proper filter apparatus for each suspension can be correct or not. For the first suspension (which doesn't requires cake washing) disc filters were recommended and for the second suspension (which requires good washing) a Nutsche Filter was recommended. What do you think about these suggestions after you have analyzed the laboratory test results?

Task 1

From the measured curves (see filtration curves above) try to compare qualitatively the filterability of the suspensions and eventually detect errors and real effects which contribute to deviations from the ideal cake formation curve.

- We have a higher filterability for the suspension on the left. Comparing for example the green curves in both diagrams we see that for the experiment on the left we have 100 g of filtrate in 40s with a pressure difference of Dp=0.6 bar. For the right diagram and with even higher pressure difference (Dp=1 bar) we need for only 50 g of filtrate 1000 s!

- For the "green" experiment on the right (Dp=1 bar) we have measurement points from the deliquoring step (see the different curve type at the end of the experiment).

Task 2

Compare 3 different methods for determining the cake permeability and the filter medium resistance by using FILOS and taking as example the first experiment of the Susp Proj2.2-1 (Dp=0.6 bar). The methods are the following: Integral method (Dp t/v =f(v)), general integral method (Dp (t-t0)/(v-v0) =f(v+v0)) and the differential method (Dp dt/dv=f(v)). What conclusions can be deduced?

In Project 2.1 we saw how we can correct the cake formation test data in order to get correct values for the cake permeability and the filter medium resistance. It could be seen that even very difficult cases could be corrected and we could get after the correction reliable values for the filtration parameters. It can be said that almost every filtration experiment needs a correction and without this correction we get wrong values of the filtration parameters. And wrong values mean a wrong characterization of the filterability of our suspension and wrong calculations of the filtration performance. FILOS big advantage is among others that it enables in a very user friendly way the correction of the filtration experiments and the correct determination of the cake permeability, the filter medium resistance and the cake compressibility.

Taking the data of the first experiment of the Suspension Proj2.2-1 (Dp=0.6 bar) and analyzing by using the integral cake formation equation using the option t_0=0 and without any corrections we get the following results (see fig. 20)

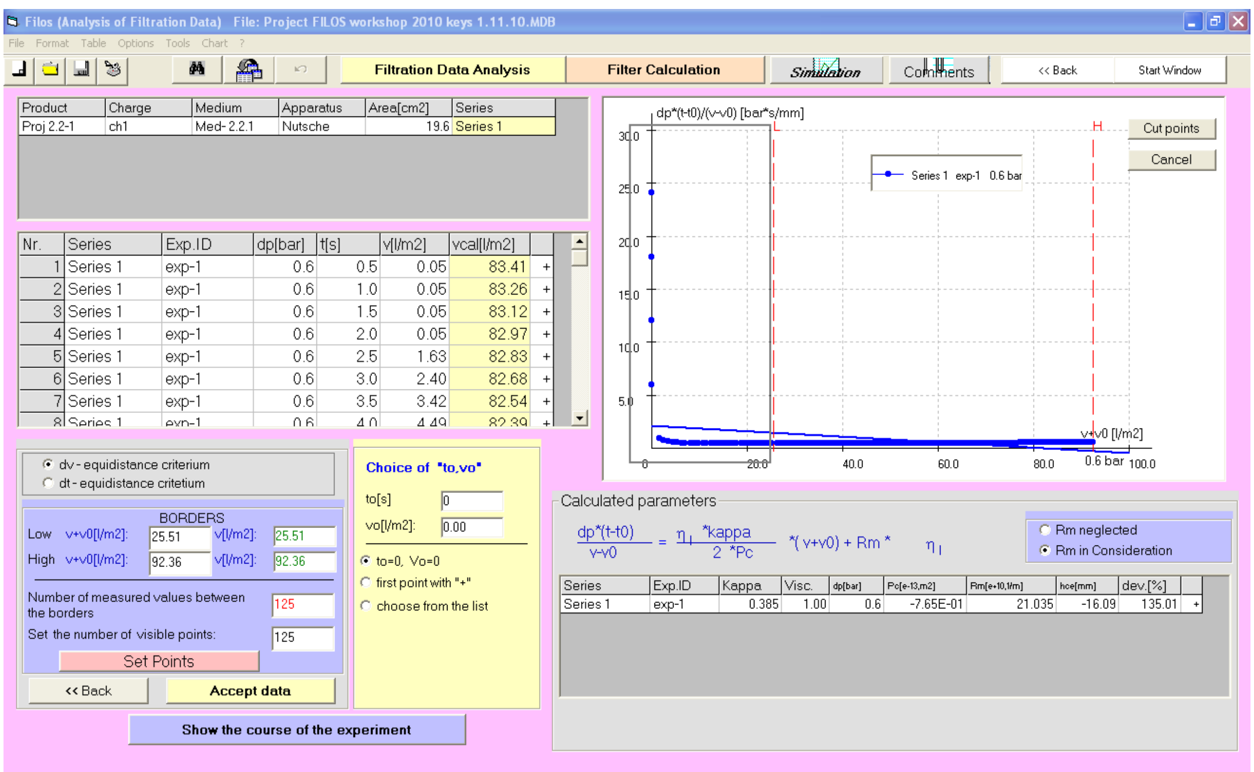


Fig. 20: The analysis of the filtration experiment with the integral method (option t0=0) and without any corrections

The wrong measurements at the beginning of the experiment result in even a negative cake permeability! The program enables the exclusion of the first measurements in two ways: By moving the red line to the right (see fig. 20) and clicking *Set Points*, so that all not good measurements (measurements on the left of the red line) can be neglected from the regression analysis or by bordering via mouse-right clicking the points which have to be neglected and clicking the command button *Cut points* on the right upper part of the diagram.

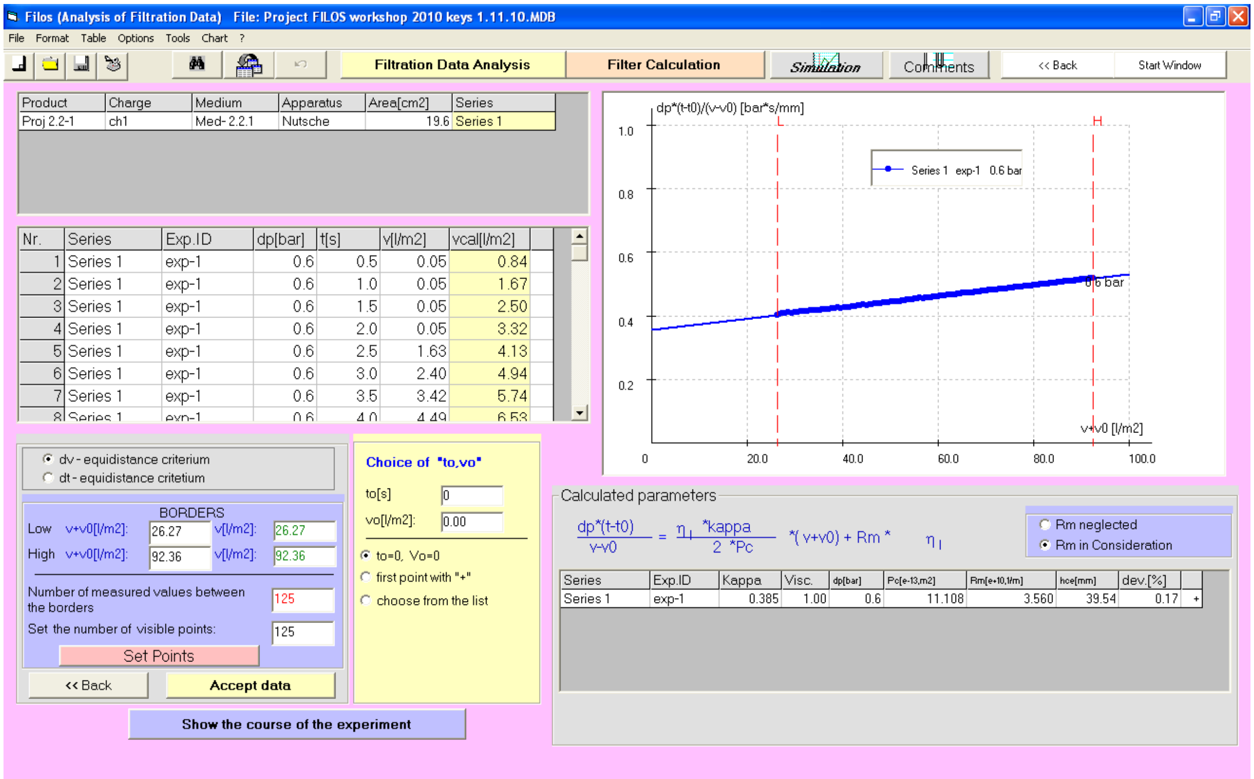


Fig. 21: The analysis results of the filtration experiment by using the integral method (option t0=0) after having corrected the wrong measurements at the beginning of the experiment.

After correcting the first wrong measurements we have the results as illustrated in fig. 21. As can be seen, we get from the corrected data and using the integral cake formation equation (Option t0=0, v0=0) the following values for the filtration parameters: Pc= 11.1 and Rm=3.56 (I recommend to use for the cake permeability only the number in front of "10^{-13} m^2" and for the filter medium resistance Rm the number in front of "10^{+10} m^{-1}").

But the problem is the following: By using the integral method (option t0=0, v0=0) although we don't consider the excluded wrong first measurements in the regression analysis, their influence is still there! In other words the measurement points which we consider include also an error due to these wrong first measurements! That is a characteristic of the integral method! That's why the correct integral method is the General integral method (t0>0). This general integral method is selected by choosing the option *first point with "+"* instead of the option *t0=0, v0=0*.

In fig. 22 we see the results of the General integral method (option *first point with "+")* after having corrected some of the wrong measurements at the beginning of the experiment. As can be seen, we get now pc=8.66 and Rm=3.07 instead of pc=11.11 and Rm=3.56.

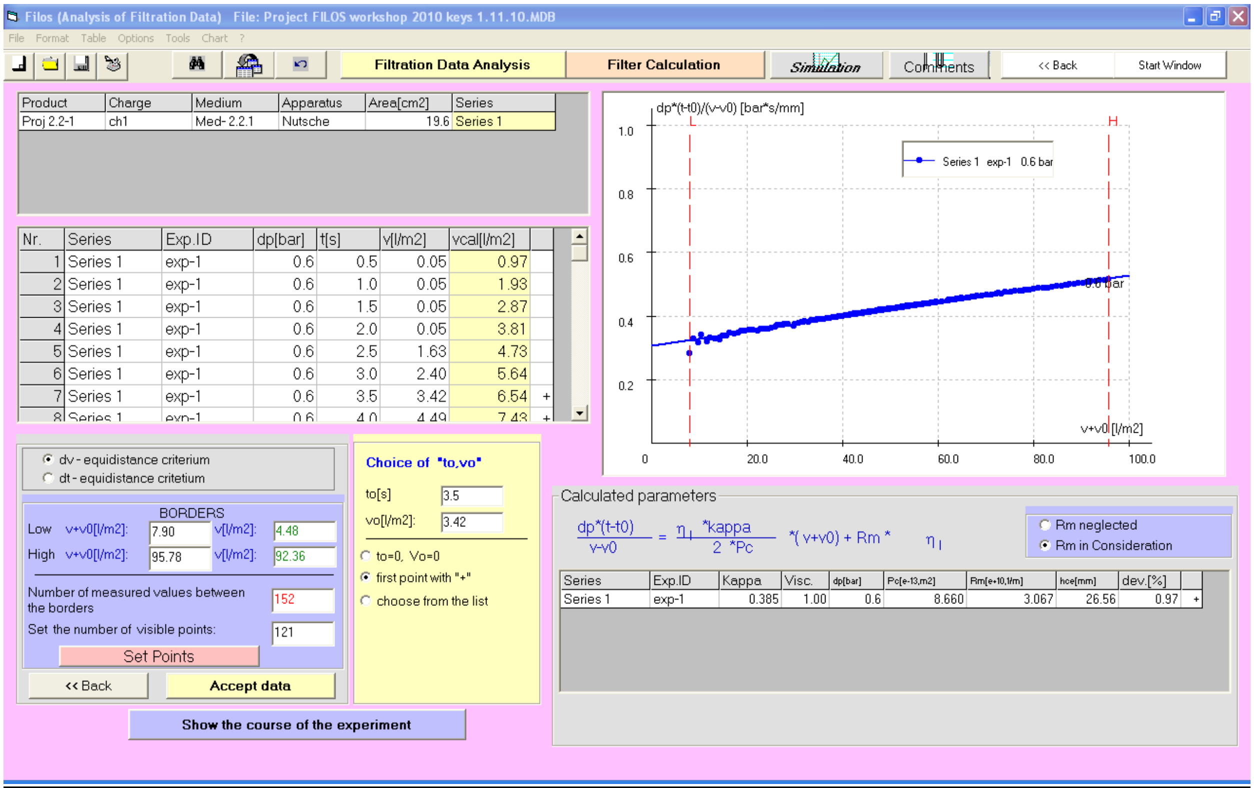


Fig. 22: The analysis results of the filtration experiment by using the general integral method (option *first point with "+"*) after having corrected the wrong measurements at the beginning of the experiment.

As third method for the analysis of the cake formation experiments is the differential cake formation equation (see fig. 23). The advantage of this method is that the influence of the first wrong measurements is considerably less than when using the above described integral methods. In fig. 23 we had removed only the first measurement and we get the following results: pc=8.19, Rm=2.96. That means the results by using the general integral equation and by using the differential equation are similar. Only the scattering of the measured points (as it is expected) is in case of the differential method much more than in case of the integral methods. That's why it is recommended to use the general integral method to get the cake permeability and the filter medium resistance and use the differential method sometimes when we want to detect the influence of particle sedimentation, filter medium clogging or cake under saturation.

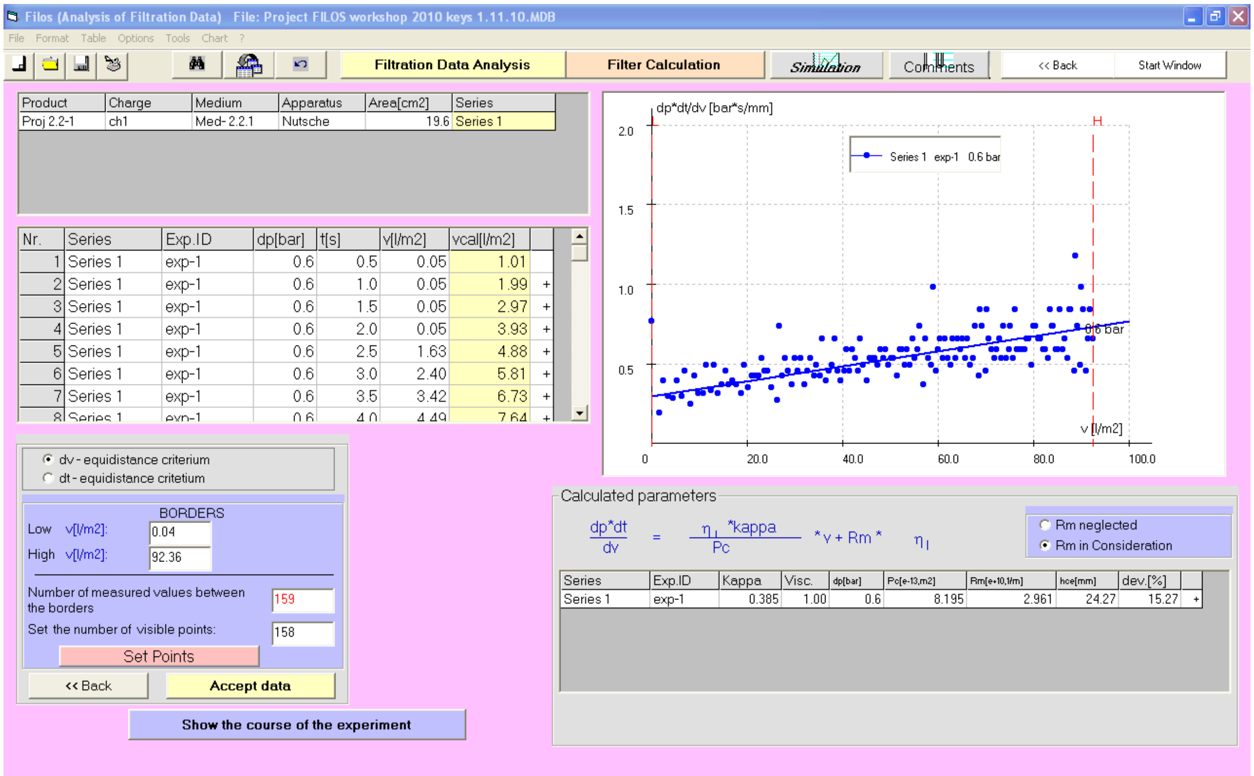


Fig. 23: The analysis results of the filtration experiment by using the differential method and practically without any correction (only the first measurement was removed).

In table below you see for this experiment a comparison of the results of the regression analysis when using the three analysis methods:

Table 2: Comparison of the determined filtration parameters by using the three different analysis methods

	Integral method with t0=0	General integral method (t0>0)	Differential method
Cake permeability pc/10-13 m2	11.108	8.66	8.195
Medium Resistance Rm/1010 m-1	3.56	3.067	2.961
Specific medium resistance hce/mm	39.54	26.56	24.27

Task 3:

Determine for both Suspensions the cake permeability pc0, the cake compressibility nc and the filter medium resistance by using the measured filtrate mass as a function of time (see excel file sheets “Susp X1” and “Susp X2”) and the data given in the table below

Suspension Name	Viscosity mother liquid/ mili Pas	Density mother Liquid/ kgm-3	Density solids/ kgm-3	Suspension Solids mass fraction/%	Cake porosity/%
Susp Proj2.2-1	1	1000	2700	32.3	46
Susp Proj2.2-2	1	1000	2500	30	65

FILOS enables the copying of measured data (filtrate mass Mf=f(t)) from an excel file and paste them to the table of the main window (Data Input window) of the module *Detailed Cake Formation*. After having entered also the material parameters (see the above table: viscosity and density of mother liquid, solids density, suspension solids concentration and cake porosity) we should always first analyze every experiment separately by selecting the option button *current experiment* and then clicking the command button *Calculate Filtration Parameters*. The analysis of every experiment separately enables the user friendly correction of the data and the accurate determination of the filtration parameters. Please don’t forget to click the *Accept data* – command button in the results window after you have corrected the measured points and after being sure that the determined parameters are the correct values. Without clicking the *Accept*-button the corrected measurements are not kept in memory and you can’t save them. <u>The program saves always what has been accepted before!!!</u> This concept has the advantage that you can “play” with different settings without losing your corrected data.

It is recommended to analyze first each experiment of the test series separately and then from the data input window (main window) by selecting the option button *current series* and clicking *Calculate Filtration Parameters* we have the results for all selected experiments of the current test series (experiments of one test series can be deselected by double clicking the experiments table and thus removing the “+” in the last column).

In fig. 24 we see the results for the suspension Proj 2.2-1. It can be seen that the determined cake permeability is almost the same for each experiment (for each pressure difference). In other words we have an incompressible filter cake. Regarding the filter medium resistance we have a significant increase of the absolute medium resistance Rm with increasing pressure difference (what is normally expected).

In fig. 25 we see the program window for the determination of the cake compressibility nc and the filter medium compressibility mc. The output of the results window (see fig. 24) is the input for this window. That means only if we have correct determination of the cake permeability and the filter medium resistance we can expect correct values for the cake compressibility nc and the filter medium compressibility mc. It can be seen that we get for this suspension a cake compressibility (nc-value) of almost zero (an evidence of cake incompressibility!). Normally it should be satisfactory if we can get correct cake compressibility and an average value of the specific filter medium resistance hce. For the calculation of the performance of the different filters (see *Filter Calculation* modules) we need the cake permeability pc0 for a pressure difference Dp0) the cake compressibility nc and the specific filter medium resistance hce0.

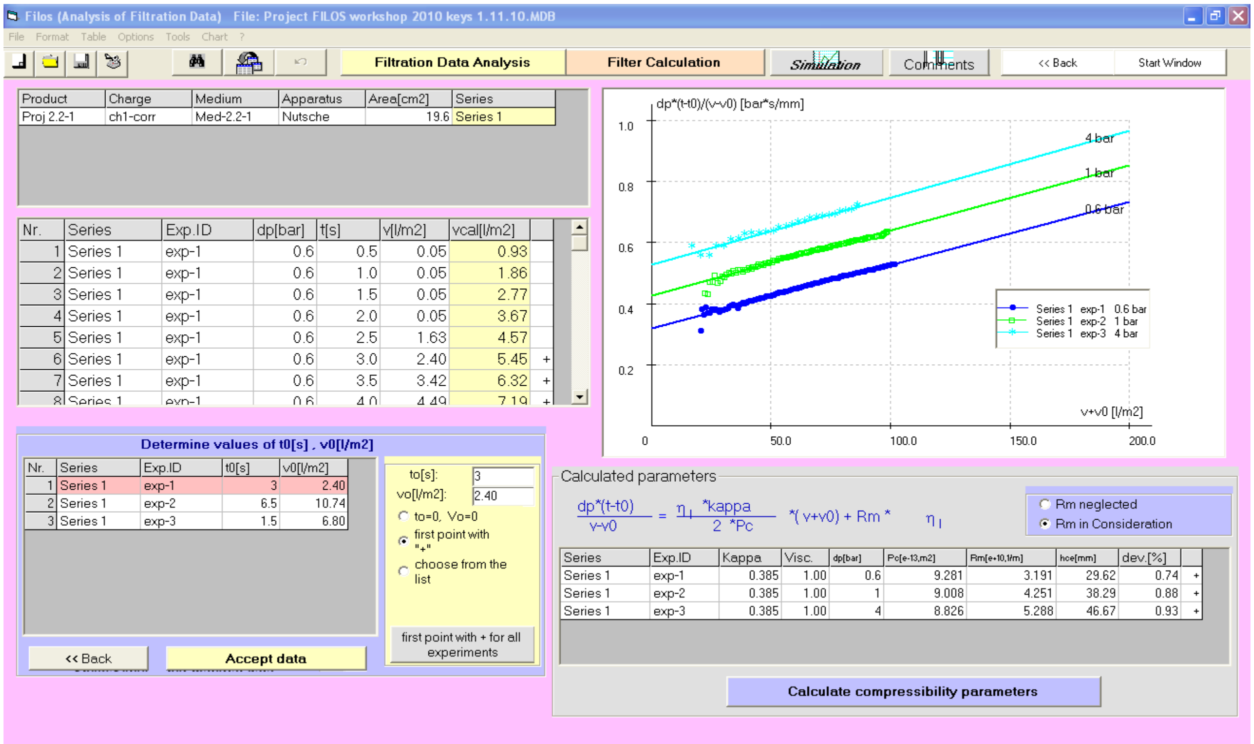


Fig. 24: Analysis results window (option *current series*) for all selected experiments of the test series (test series with the suspension Proj2.2-1).

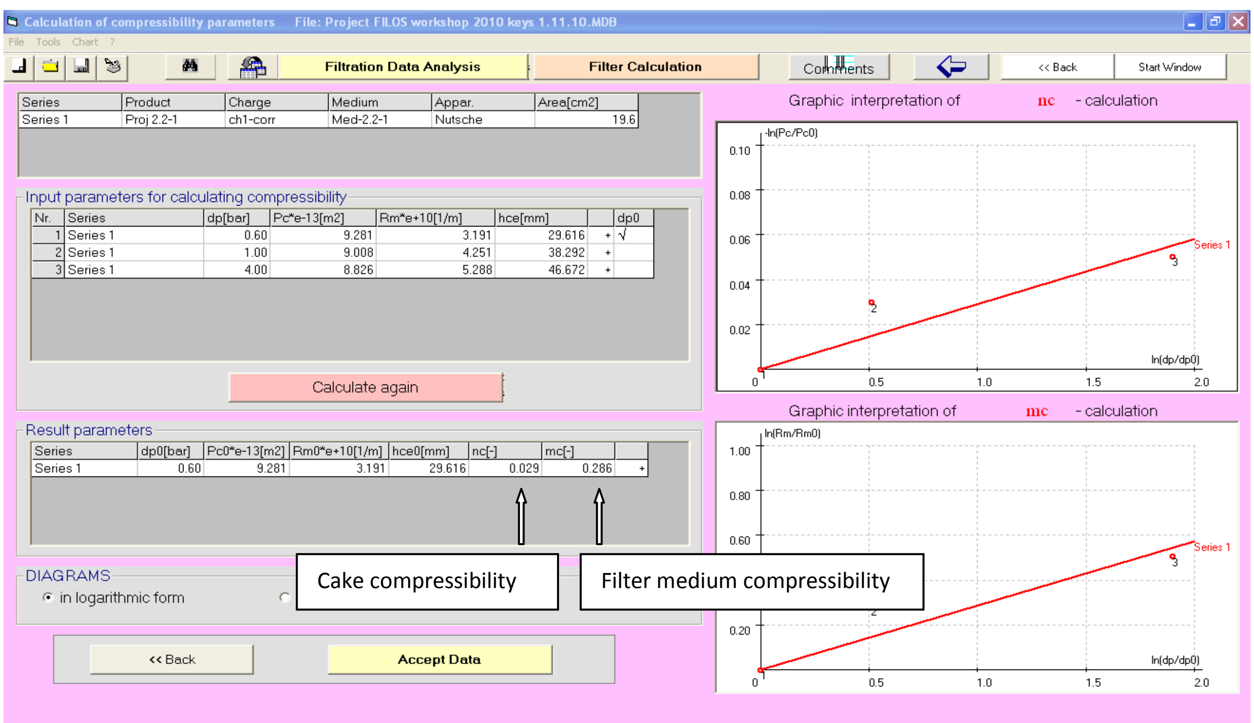


Fig. 25: Second analysis results window with the determination of the cake compressibility (nc-value) and the filter medium compressibility (mc-value). The obtaining of the cake and filter medium compressibility is possible if we have at least 2 experiments with not the same pressure difference (test series with the suspension Proj2.2-1).

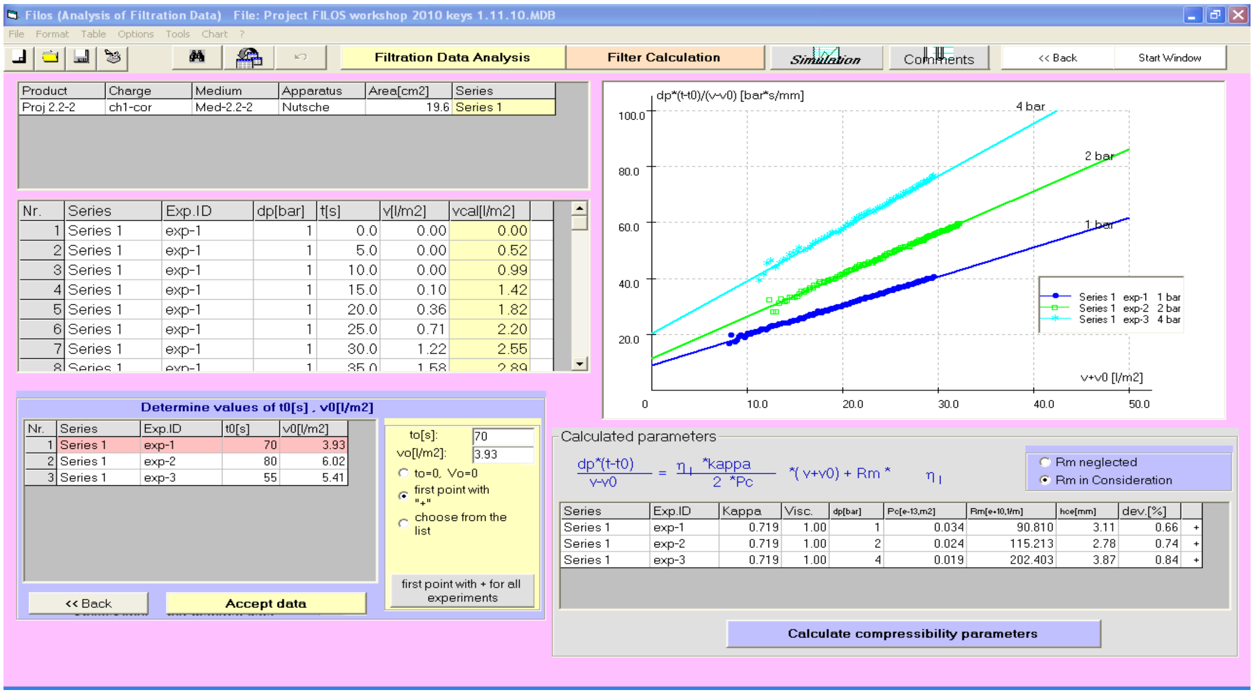


Fig. 26: Analysis results window (option *current series*) for all selected experiments of the test series (test series with the suspension Proj2.2-2).

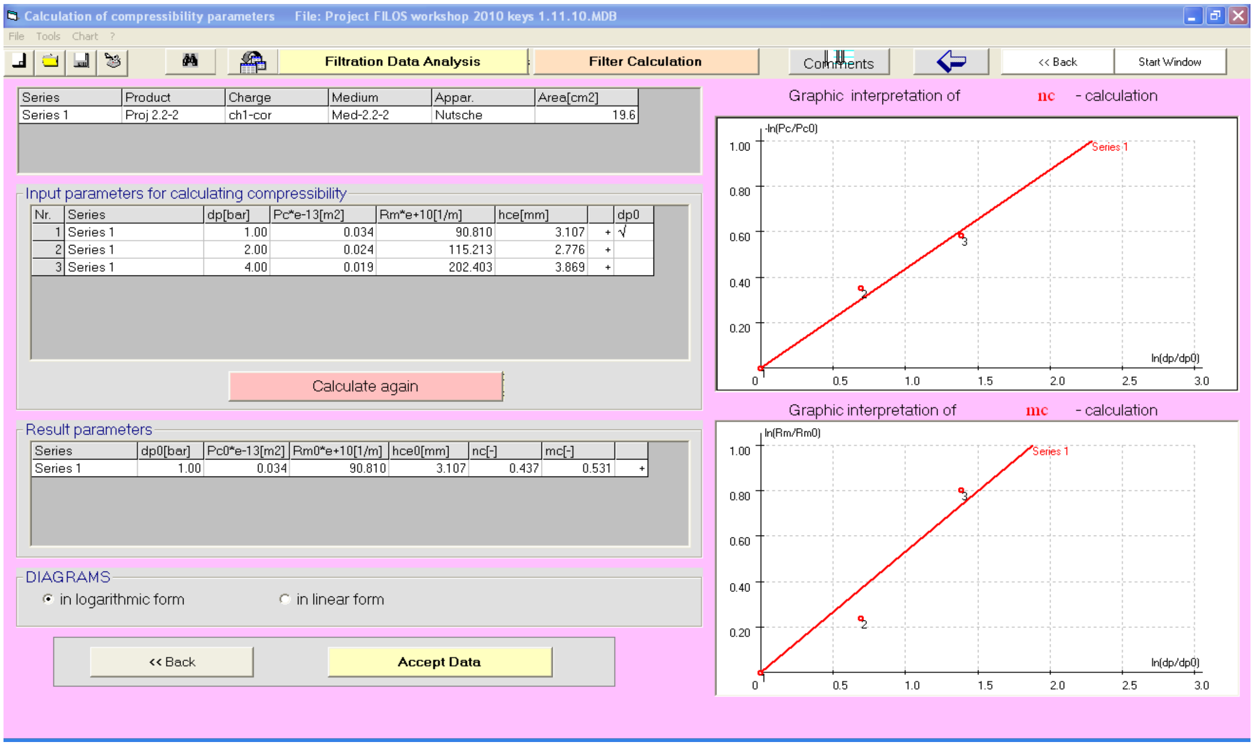


Fig. 27: Second analysis results window with the determination of the cake compressibility and the filter medium compressibility (only possible when we have at least 2 experiments with not the same pressure difference) (test series with the suspension Proj2.2-2).

In fig. 26 and fig. 27 we see the first and the second analysis results –window for the second suspension (Proj 2.2-2). The first results window for all experiments of the selected test series displays the regression curves for the 3 experiments (3 pressure differences) and below the diagram we see the determined cake permeability, the absolute and specific filter medium resistance Rm and hce. Contrary to the suspension Proj 2.2-1 we see a significant decrease of the cake permeability with increasing pressure difference (visually this can be seen from the different slopes of the three curves!), that means we have in this case a significantly compressible filter cake. This cake compressibility is determined in the second analysis window from the slope of the upper diagram (see fig. 27). The slope of the second diagram gives us the compressibility of the filter medium.

In table 3 and table 4 we see the results of the filtration parameters for the two suspensions Proj2.2-1 and Proj2.2-2.

<u>Table 3:</u> Results of the analysis of the measured filtration data for the suspension Proj2.2-1 (analysis with the general integral method)

Dp/bar	**pc/10^{-13} m^2**	**Rm/10^{10} m^{-1}**	**hce/mm**	**nc/-**	**mc/-**
0.6	8.518	3.036	25.86		
1	9.008	4.251	38.29	0.029	0.286
4	8.826	5.288	46.67		

<u>Table 4:</u> Results of the analysis of the measured filtration data for the suspension Proj2.2-2 (analysis with the general integral method)

Dp/bar	**pc/10^{-13} m^2**	**Rm/10^{10} m^{-1}**	**hce/mm**	**nc/-**	**mc/-**
1	0.034	90.81	3.11		
2	0.024	115.2	2.78	0.437	0.531
4	0.019	202.4	3.87		

<u>Task 4</u>

What values of the filtration parameters we get in case that we do not do any corrections of the measured data and what is the reason of the errors of the measured data for these two test series?

In fig. 28, fig. 29 and fig. 30 we see the analysis results for the suspension Proj2.2-1 and in fig. 31, 32 and 33 for the suspension Proj2.2-2 <u>without any corrections</u> for the 3 analysis options (integral with t0=0/ general integral (t0>0) / differential method). As can be seen all methods deliver wrong values of the filtration parameters if we do not do the correction of the measurements as it is described in Task 2 of this project and in Project 2.1. The “best” results (although also not correct) we get by the general integral method. For both suspensions the reason for these bad results are the wrong measurements at the beginning of the experiments.

Comparing the corrected results (see task 3) with the results of the not corrected data (see current task) we want to emphasize the importance of the correction of the cake formation test results as necessity to get accurate values for cake permeability, filter medium resistance and cake compressibility.

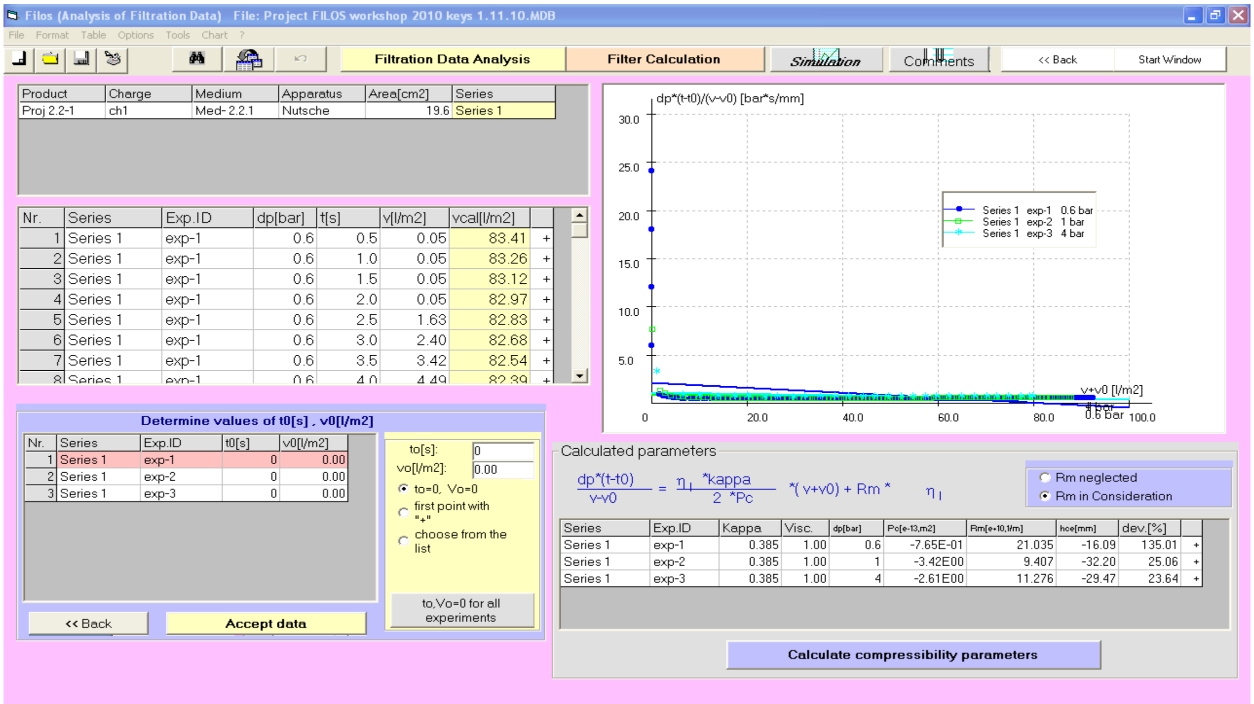


Fig. 28: Common analysis of the 3 filtration experiments by using the integral method (option t0=0) and without any corrections (suspension Proj2.2-1). We see negative permeability values for all experiments!

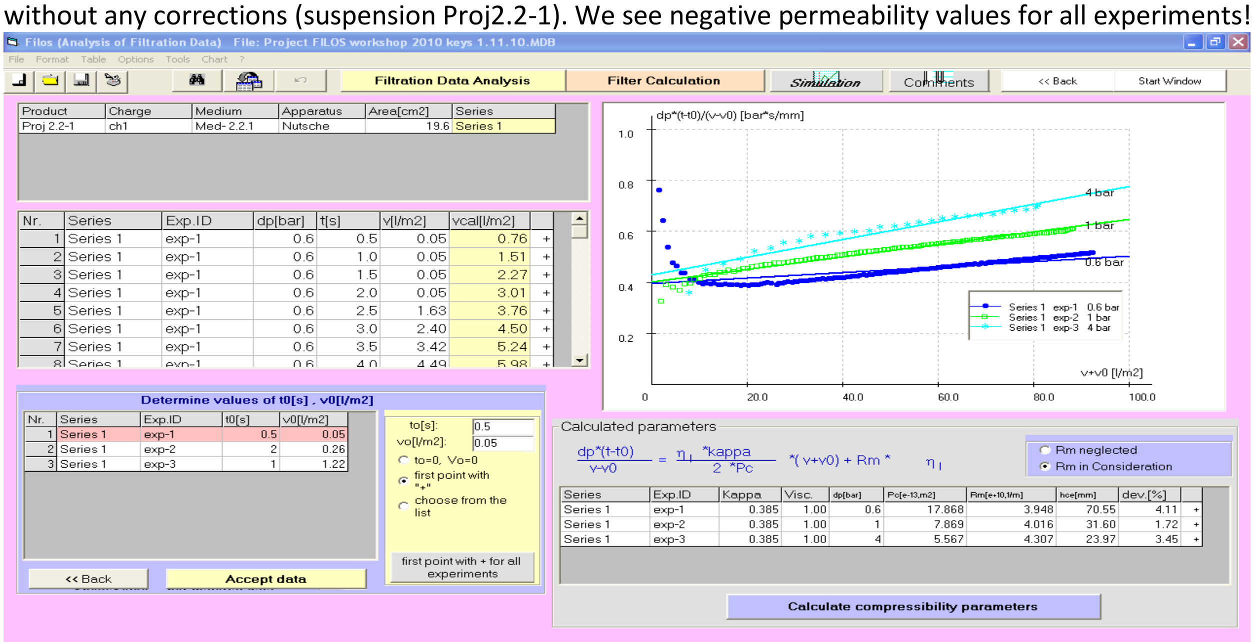


Fig. 29: Common analysis of the 3 filtration experiments by using the general integral method (option first point with "+") and without any corrections (suspension Proj2.2-1). Although corrections are needed to get accurate results we can see the advantages of the general integral method by comparing with the results in fig. 28.

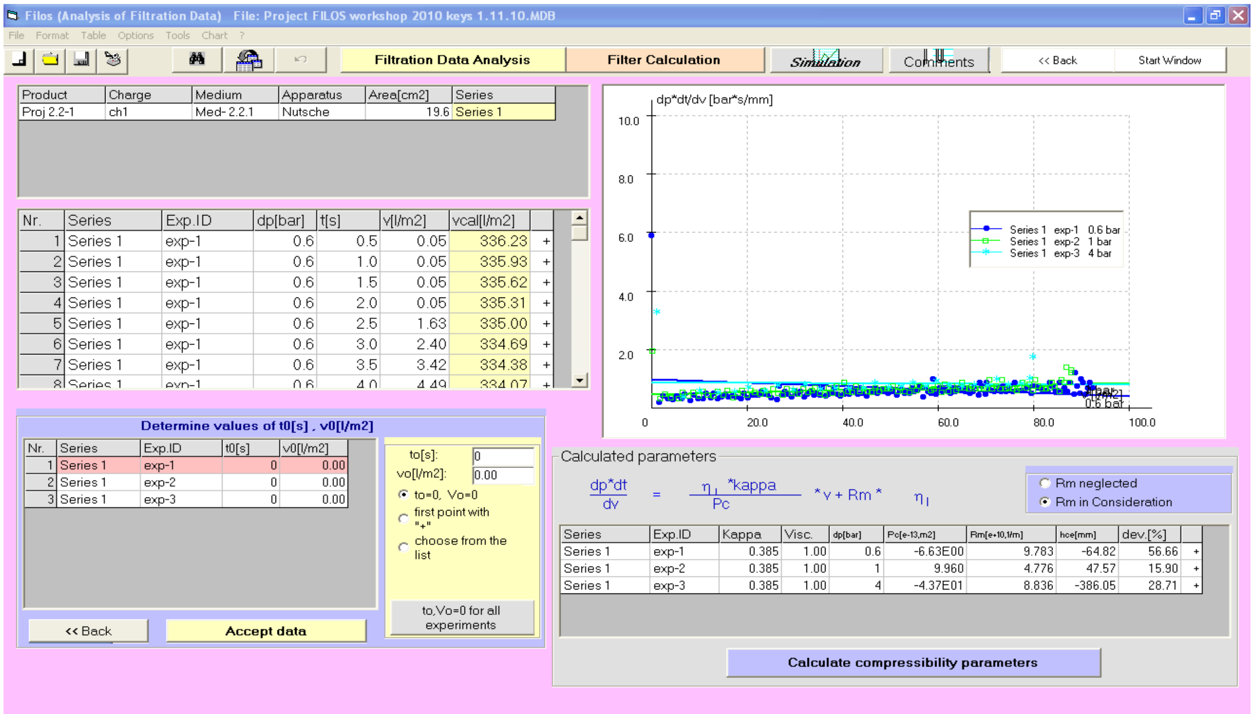


Fig. 30: Common analysis of the 3 filtration experiments by using the differential method and without any corrections (suspension Proj2.2-1). We see that also with this method the results can not be used if we don't do any corrections.

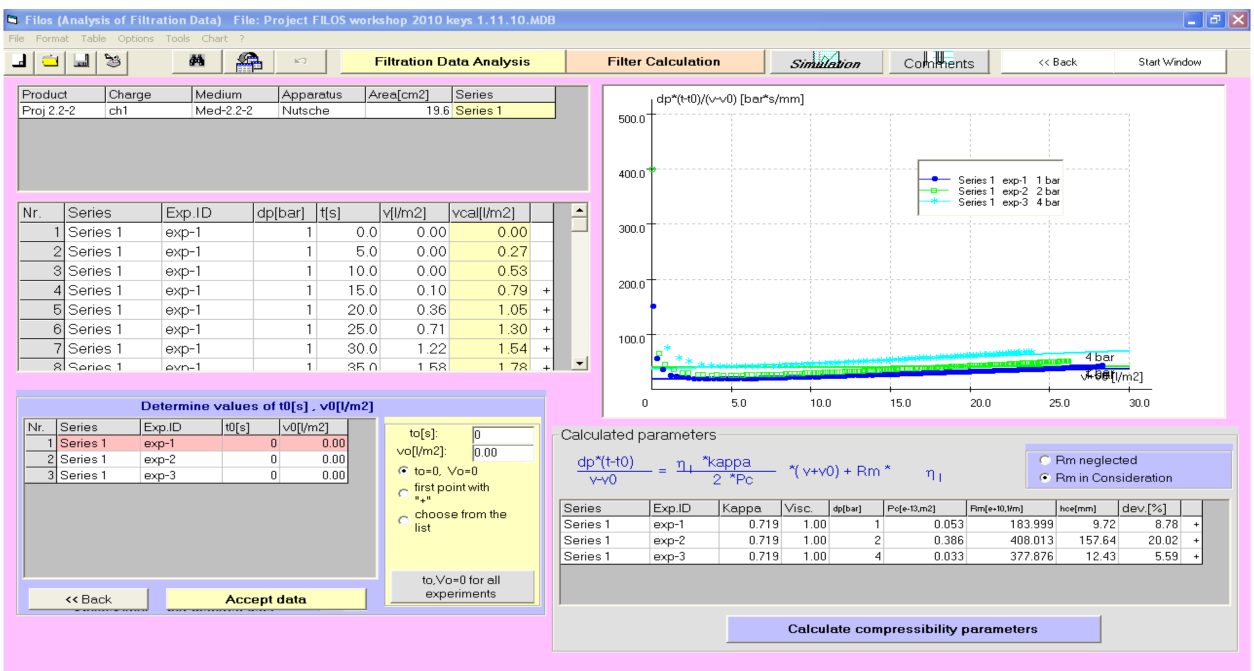


Fig. 31: Common analysis of the 3 filtration experiments by using the integral method (option t0=0) and without any corrections (suspension Proj2.2-2).

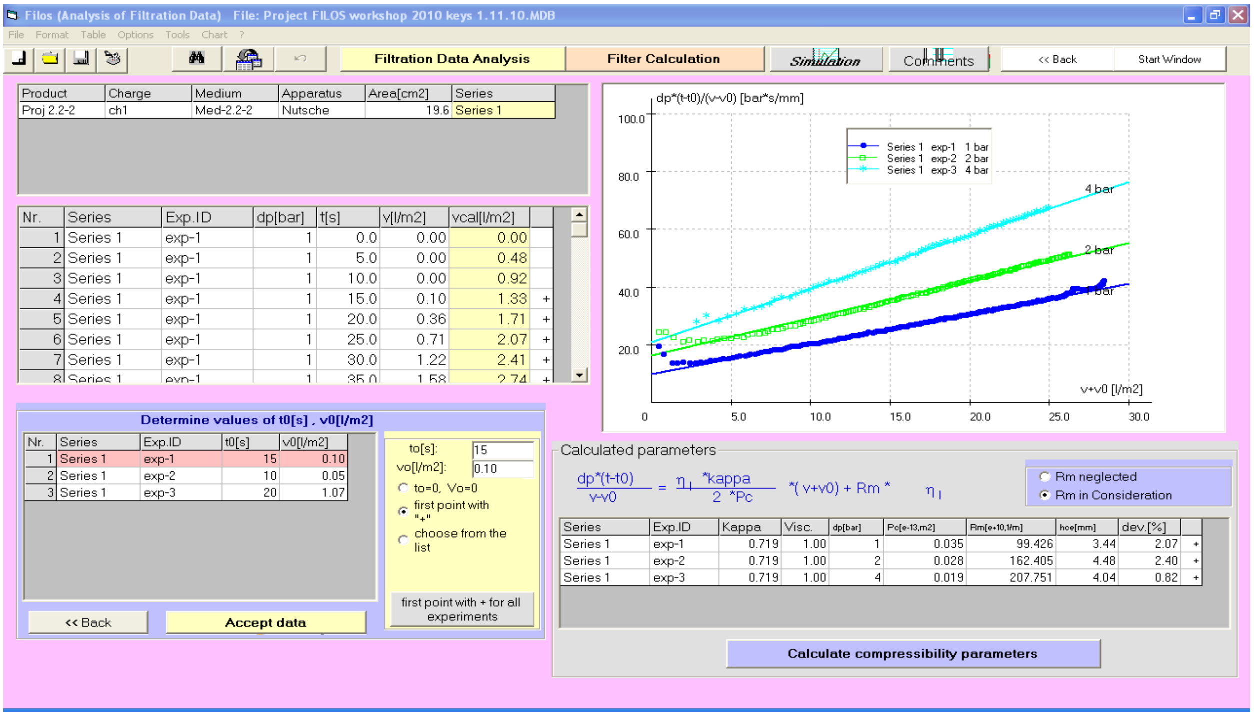


Fig. 32: Common analysis of the 3 filtration experiments by using the general integral method (option first point with "+") and without any corrections (suspension Proj2.2-2). We see that in this case even without any corrections we get reliable values for the filtration parameters.

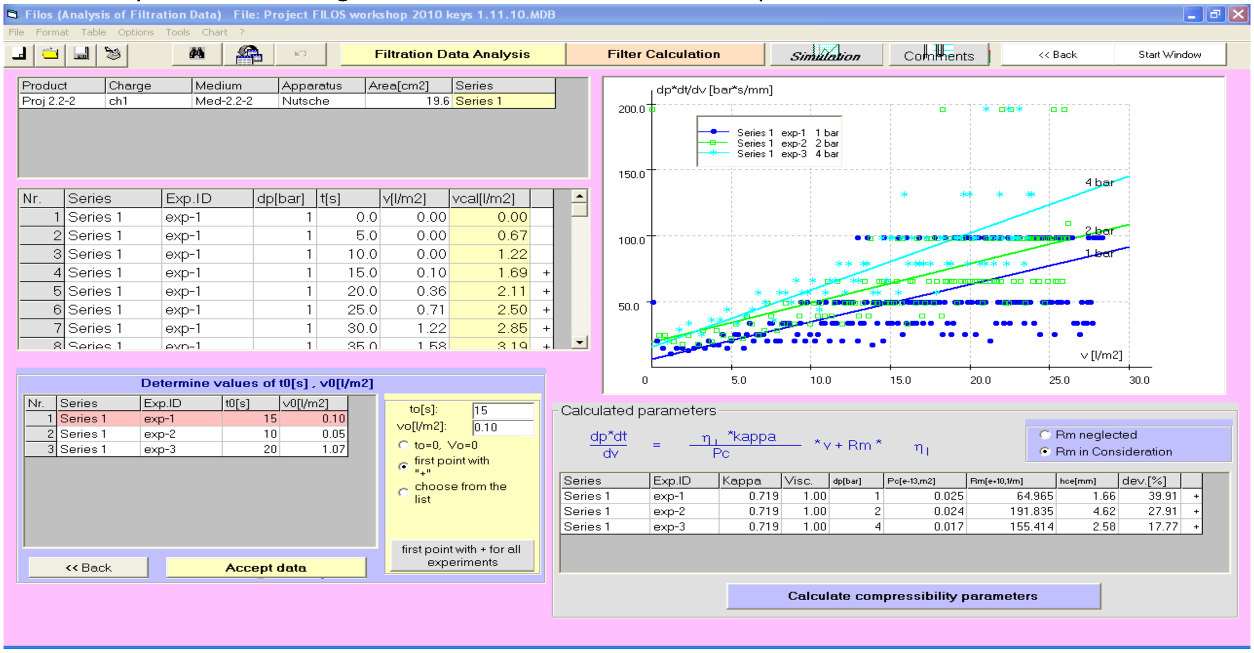


Fig. 33: Common analysis of the 3 filtration experiments by using the differential method and without any corrections (suspension Proj2.2-2). We see a big scattering of the data.

Task 5

Why it is better to include in the y-axis parameter of the theory based diagram the pressure difference Dp? How we can recognize the cake compressibility from the curves of one test series in the theory based diagram?

By including the pressure difference in the y-axis parameter for the theory based diagram (that means instead of t/v using Dp t/v) we have

- as first advantage: from the slope of the curves of one test series we can see if the cake is compressible or not. If the higher the pressure difference the higher the curve slope then in this case we have a compressible filter cake. Incompressible cake means parallel lines for the tests with different pressures (compare fig. 24 and fig. 26 as examples for incompressible and compressible filter cake).
- as second advantage: we can compare from the diagram the filter medium resistance Rm for different experiments. The smaller the ordinate intersection length the smaller the filter medium resistance.

Such judgments can't be done in case we do not include the pressure difference Dp in the y-axis parameter.

Task 6

What can be said about the filter media, which were selected for both suspensions? How the absolute filter medium resistance depends on the pressure difference Dp?

Important parameter for judging the filter medium regarding its resistance during the cake formation is the hce-value (medium resistance related to the cake resistance: hce=pc*Rm with pc=1/rc and rc the cake resistance). From table 3 we can judge that the filter medium used for the filtration of the suspension Proj2.2-1 (hce-values between 26 mm and 47 mm) has only then too high medium resistance if we use a filter apparatus with a relatively small cake height (for example continuous Belt or Drum or Disc filters with a cake height of let us say 20 to 50 mm. But if we use for example a nutsche filter with a cake height of let's say 500 mm then this filter medium would be ok. The filter medium used for the filtration of the suspension Proj2.2-2 has hce-values approx between 3 and 4 mm. Having in mind that the formed cake has a relatively very low permeability, although the hce-values are much smaller than the hce-values of Proj2.2-1 we can say that the medium resistance for this suspension is too high. For suspensions with such a low cake permeability normally the hce-value should be smaller than 1 mm. Exceptions are cases we don't want to allow any solids in the filtrate and that's why we deliberately use filter media with relatively high resistance.

Task 7

One of the reasons why you did this analysis for Proj 2.2 was mainly to find out if the suggestions of the filter manufacturers regarding the proper filter apparatus for each suspension can be correct or not. For the first suspension (which doesn't requires cake washing) disc filters were recommended and for the second suspension (which requires good washing) a Nutsche Filter was recommended. What do you think about these suggestions after you have analyzed the laboratory test results?

The first suspension (Proj 2.2-1) has a relatively very high cake permeability of approximately pc=10 and it will be difficult to keep a homogeneous suspension in the trough due to the high sedimentation tendency. This can lead to an inhomogeneous filter cake (different cake heights in one segment) and to a bad deliquoring behavior. Better filter apparatus would be a belt or pan filter in this case.

Regarding the second suspension (Proj 2.2-2) we have a very low cake permeability (pc=0.03) and a not negligible cake compressibility (nc=0.44). By using a filter nutsche which demands a relatively thick filter cake we will have extremely high filtration and washing times, that means a very high cycle time. The cake will have tendency to cracking and the deliquoring will not be sufficient. A better filter apparatus in this case is the Filter Press with a formation of a relatively thin cake (smaller cycle time!) and a possibility of cake squeezing which will give a homogeneous cake washing and a lower cake moisture content.