06-665 Process Systems Modeling

Project: **Optimizing Tray-Layout design for preventing mal-distribution**

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I. Abstract

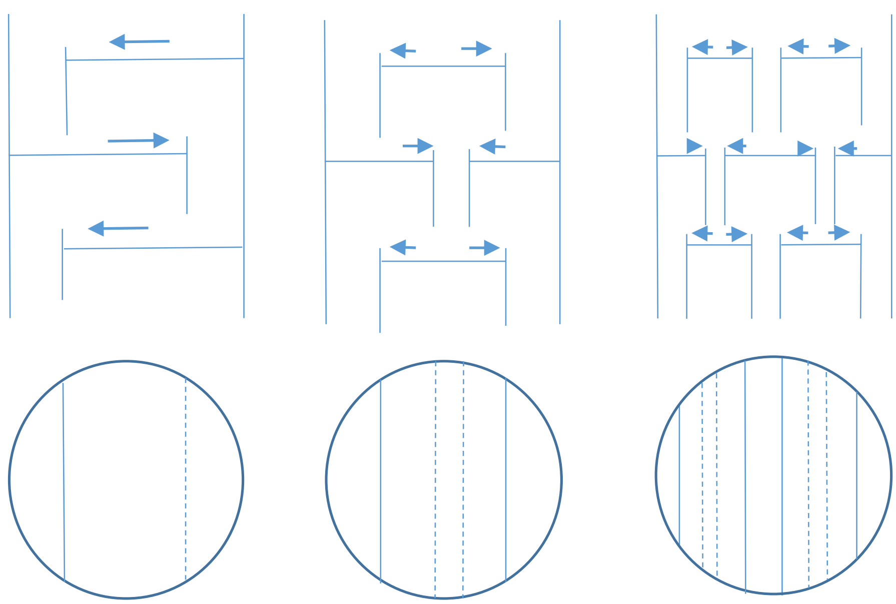
In order for a tray column to function properly at an optimum capacity and efficiency as well, multi-pass trays need to be designed in a way that ensures that liquid and vapor flows are balanced properly. When the vapor flow is disproportional to the liquid flow in different areas of the tray pinching and poor separation can occur. Four pass trays are symmetrical across the centerline but the outer passes are not symmetrical. The model proposed provides simple rules and equations to ensure that a 4 pass tray layout is optimized for minimizing mal-distribution resulting in properly balanced vapor and liquid flows.

II. Introduction and Problem Statement

Single pass and two pass trays are very common and fairly simple to design since the flow paths are symmetric. As columns get larger the number of passes that are required for proper functioning increase as well. The reasons for the need for an increase in passes are that due to an increase in column diameter the tray panel lengths in one and two pass trays become larger and hence the liquid level on each panel becomes uneven which results in non-uniform pressure drop and hydraulics across a tray. In general, the objective is to keep the number of passes as low as possible since it would be economically favorable to do so. Summers [1] suggests that once the weir loading is higher than 12 gpm/in the number of passes would need to be increased.

Two pass trays have perfect symmetry with the entire liquid remixing before it enters the center downcomer which makes it completely resistant to mal-distribution. However four pass trays even though they are symmetrical along the central axis have non symmetry along the outer passes and hence is prone to mal-distribution.

Four pass trays have a configuration consisting of two different types of trays that alternate. One type has two off-center downcomers and the other has two side downcomers and a center downcomer.



A: SINGLE PASS B: TWO PASS C: FOUR PASS

FIGURE 1: TRAYS WITH DIFFERENT NUMBER OF PASSES

A common term to evaluate the measure of liquid and vapor balance is the vapor/liquid flow ratios (V/L) across each panel on the tray.

Bolles [2] has defined a term, distribution ratio as the maximum liquid/vapor (L/V) ratio and has recommended keeping this distribution ratio less than 1.2 in order to achieve good tray efficiency while Summers [1] has proposed a tighter criterion of 1.1.

Variation in the L/V ratio form pass to pass have an adverse effect not only on tray efficiency, but also on tray capacity. Regions where mal-distribution increases the vapor or liquid loadings may be pushed into flooding, while other regions where the loads are reduced have surplus capacity. Passes in which the L/V ratio is higher are likely to experience excessive liquid loads and hence premature downcomer choke flooding, while those in which the L/V ratio is low are likely to experience excessive vapor loads and therefore premature jet or downcomer backup flooding. Either of those cases would decrease the overall tray capacity.

The objective of the proposed model is to achieve minimum distribution ratio and all the factors influencing this distribution have been thoroughly discussed and accounted for in the next panel.

In this project we aim to obtain a minimum distribution ratio and optimize the tray layout in order to obtain the same.

III. Literature Survey

Bolles[2] has where the liquid/vapor flow ratios differ among passes, the effective (mean) mass transfer efficiency for the overall tray may be less than that obtained when the phases are equally distributed.

It was concluded from studies that the mean efficiency for any reasonable two-pass tray design is essentially equal to the arithmetic average of the predicted efficiencies for the passes.

Sample case results for four pass trays are below:

Pass	1	2	3	4
L/V	0.56	1.11	1.11	0.56
% flood	68	70	70	68
% efficiency	88	78	78	88
Distribution ratio	1.96			
Average efficiency	83			
Mean efficiency	69			
Mean average efficiency	0.83			

Pass	1	2	3	4
L/V	0.82	0.84	0.84	0.82
% flood	69	69	69	69
% efficiency	81	81	81	81
Distribution ratio	1.02			
Average efficiency	81			
Mean efficiency	81			
Mean average efficiency	1			

Bolles [2] used a multipass model to produce the above results and we can clearly see that the mean efficiency is much higher for a close to perfect tray column as compared to a mal-distributed column.

Kister *et al.* [3] have very rigorously developed a model to measure this mal-distribution and have shown the effect this said mal-distirbution has on tower operations. Consequences of mal-distribution include that of instability of a column operating at a throughput slightly beyond design conditions and premature flooding near the bottom of such columns.

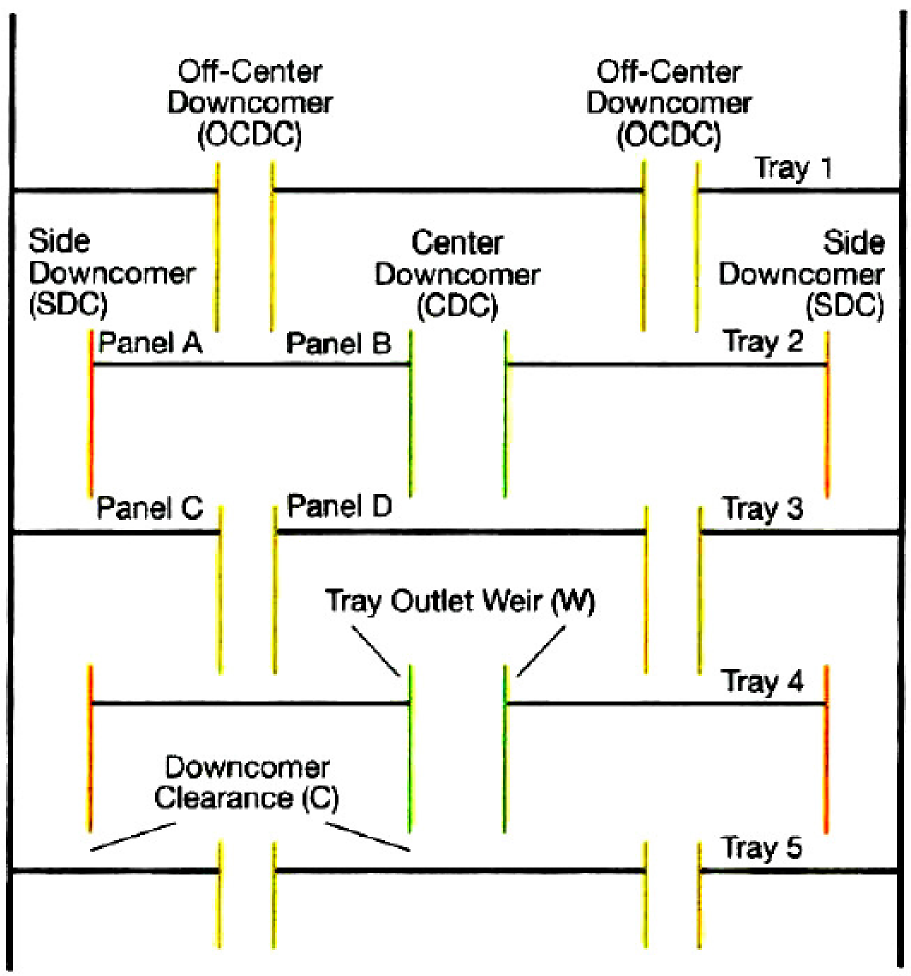
Summers [1] has provided detailed guidelines on how to go about designing four pass trays in order to make them function at optimum capacity and efficiency, the details of which have been elucidated and equations formulated from in the next section.

IV. Mathematical Model

1. Nomenclature and tray layout basics

A standard tray consists of a tray deck which generally have sieve holes or valves and a downcomer which is designed to disengage additional vapor in the liquid froth mixture that leaves a tray. Other features include a downcomer clearance (C) which is a vertical gap between the lower edge of the downcomer and the tray deck. The purpose of the tray outlet weir (W) is to maintain a desired liquid level on the tray deck.

Four-pass trays have additional features. They have three different type of downcomers. Side downcomers (SDC), Off-center downcomers (OCDC) and center downcomers (CDC). The off-center downcomer is asymmetric. The side that is closer to the column wall has a smaller weir length than the side that is closer to the center. There are also four different types of active area panels on four pass trays.



2. Tray Layout optimization objectives:

    a. The L/V ratios should be as close as possible across all panels

       Having equal L/V ratios across each panel would ensure no pinching and each panel would have similar separation characteristics

    b. Inlet downcomer velocities should be identical for all downcomers

       The tray should be designed in a way that matches the process requirements in terms of flooding capacity and pressure drop. This would imply the requirement of having equal inlet downcomer velocities.

    c. Flow path length across each panel should be equal

       There are two different schools of thought in tray layout design. Equal bubble area and equal flow path length. Both methodologies have its own advantages and disadvantages. Equal flow path length design is the most commonly used method and is used in this model. However the equal bubble area method could be easily adopted as well.

3. Significance of the objectives and how they would be achieved:

    a. Equal L/V ratios

       Weir loading is defined as the volumetric flow across a unit length of the weir. The crest of the liquid over a weir is directly proportional to the weir load to the 2/3rd power. This crest of liquid directly affects the hydraulic resistance for the vapor flow. Summers [1] has suggested that the method of properly balancing the weir loadings would comprise of making the weir loading for the side and center downcomer constant along with the weir loads on either side of the downcomer.

       This could be done by making the effective length of the respective downcomers shorter via picketing.

       The liquid load would also need to be split in proportion to the active areas that the liquid is flowing into. Picketing and hence maintaining equal weir loads would ensure that this happens as the split of liquid is directly proportional to the weir length of the weir that it is flowing over.

       The vapor would distribute in proportion to the active areas as long as the liquid level is uniform as it will flow into the path of least resistance.

       This would then ensure equal liquid/vapor ratio across each tray panel.

b. Equal downcomer inlet velocities

The downcomers must match the process requirements and hence each individual downcomers are desired to have identical inlet velocities. Different velocities would result in different capacities in different sections of the column which in turn would result in premature flooding and hence overdesigning of the column.

The areas of the downcomers should hence be made proportional to the active areas that feed the liquid into the respective downcomers

c. Equal flow path length

The flow path length being the cross sectional length of each panel must be kept equal in order to have similar residence times in each pass which in turn is required in order to have similar mass transfer taking place in each pass. This would avoid the chance of pinching and hence would result in overall better efficiency as compared to trays not designed with the equal flow path method.

This can be ensured by placing the off center downcomer appropriately.

4. Model and solver: NLP problem solved using CONOPT

The description of the solver obtained from its website follows below:

CONOPT is a feasible path solver based on the old proven GRG method with many newer extensions. CONOPT has been designed to be efficient and reliable for a broad class of models. The original GRG method helps achieve reliability and speed for models with a large degree of nonlinearity, i.e. difficult models, and CONOPT is often preferable for very nonlinear models and for models where feasibility is difficult to achieve. Extensions to the GRG method such as preprocessing, a special phase 0, linear mode iterations, and a sequential linear programming and a sequential quadratic programming component makes CONOPT efficient on easier and mildly nonlinear models as well. The multi-method architecture of CONOPT combined with build-in logic for dynamic selection of the most appropriate method makes CONOPT a strong all-round NLP solver.

5. Nomenclature

downcomer: All the downcomers, Side downcomer (SDC), Center downcomer (CDC) and off-center downcomer (OCDC)

panel: Panel 1 to 4 (A to D in figure)

R: Radius of the tray

sideDCAreaPercentage: Area of the side downcomer as a percentage of the total downcomer area

DCTotalArea: Total downcomer area on a tray

$DCArea_{downcomer}$: Downcomer area of the various downcomers

$DCAreaD_{downcomer}$: Distance of downcomer cord from the central axis of the tray

$DCAreaTheta_{downcomer}$: The angle the downcomer cord forms with the center of the tray circle

$DCCordWidth_{downcomer}$: The top cord width of the downcomer

$DCBottomCordWidth_{downcomer}$: The bottom cord width of the downcomer

$DCCordPosLeft_{downcomer}$: The position of the left cord of the downcomer with reference to the leftmost point of the column.

$DCCordPosRight_{downcomer}$: The position of the right cord of the downcomer with reference to the leftmost point of the column.

$DCCordPosFromCenterLeft_{downcomer}$: The position of the left cord of the downcomer with reference to the center of the tray

$DCCordPosFromCenterRight_{downcomer}$: The position of the right cord of the downcomer with reference to the center of the tray

$DCCordThetaLeft_{downcomer}$: The angle that the left cord of the downcomer with reference to the left most point of the tray makes with the central of the tray circle

$DCCordThetaRight_{downcomer}$: The angle that the right cord of the downcomer with reference to the left most point of the tray makes with the central of the tray circle

$DCCordLeftArea_{downcomer}$: The area that is formed to the left of the left cord of the downcomer with reference to the left most point in the column

$DCCordRightArea_{downcomer}$: The area that is formed to the left of the left cord of the downcomer with reference to the left most point in the column

OCDCCentralAxis: The position of the central axis of the off center downcomer

$PanLeftCordPos_{Panel}$: The position of the left cord of the panel with reference to the leftmost point of the column

$PanRightCordPos_{panel}$: The position of the right cord of the panel with reference to the leftmost point of the column

$PanArea_{panel}$: The area of the tray panel

$PanAreaPosFromCenterLeft_{panel}$: The position of the left cord of the panel with reference to the center of the tray

$PanAreaPosFromCenterRight_{panel}$: The position of the right cord of the panel with reference to the center of the tray

$PanAreaThetaLeft_{panel}$: The angle that the left cord of the panel with reference to the left most point of the tray makes with the central of the tray circle

$PanAreaThetaRight_{panel}$: The angle that the right cord of the panel with reference to the left most point of the tray makes with the central of the tray circle

$PanAreaLeftArea_{panel}$: The area that is formed to the left of the left cord of the panel with reference to the left most point in the column

$PanAreaRightArea_{panel}$: The area that is formed to the left of the right cord of the panel with reference to the left most point in the column

6. Optimization problem

min

$$z = 0.5*((sideDCAreaPercentage/(50-sideDCAreaPercentage))-(PanArea_{s1}/PanAreas_{s2}))$$
$$+ 0.5 * ((sideDCAreaPercentage/(50-sideDCAreaPercentage))-(PanArea_{s3}/PanArea_{s4}))$$

This objective function would ensure that the downcomer areas are in proportion to the panel areas that the liquid flowing into. This would ensure

s.t

Constraints for the area of the side downcomers

$$DCAreaD_{SDC} = R - DCCordWidth_{SDC}$$
$$DCAreaTheta_{SDC} = 2 * arccos\left(DCAreaD_{SDC} / R\right)$$
$$DCArea_{SDC} = \left(\left(R^2\right)/2\right) * \left(DCAreaTheta_{SDC} - sin \left(DCAreaTheta_{SDC}\right) \right)$$

Constraints for areas of the remaining downcomers

$$DCTotalArea = DCArea_{SDC} * 100 / sideDCAreaPercentage$$
$$DCArea_{CDC} = 2 * \left(50 - sideDCAreaPercentage\right) * DCTotalArea / 100$$

$$DCArea_{OCDC} = 0.5 * DCTotalArea$$

Constraints for area and cord width of the center downcomer

$$DCCordPosLeft_{CDC} = R - \left(DCCordWidth_{CDC} / 2.\right)$$

$$DCCordPosRight_{CDC} = R + \left(DCCordWidth_{CDC} / 2.\right)$$

$$DCCordPosFromCenterLeft_{CDC} = R - DCCordPosLeft_{CDC}$$

$$DCCordPosFromCenterRight_{CDC} = R - DCCordPosRight_{CDC}$$

$$DCCordThetaLeft_{CDC} = 2 * arccos\left(DCCordPosFromCenterLeft_{CDC} / R\right)$$

$$DCCordThetaRight_{CDC} = 2 * arccos\left(DCCordPosFromCenterRight_{CDC} / R\right)$$

$$DCCordLeftArea_{CDC} = \left(\left(R^2\right) / 2\right) * \left(DCCordThetaLeft_{CDC} - sin\left(DCCordThetaLeft_{CDC}\right)\right)$$

$$DCCordRightArea_{CDC} = \left(\left(R^2\right) / 2\right) * \left(DCCordThetaRight_{CDC} - sin\left(DCCordThetaRight_{CDC}\right)\right)$$

$$0 = DCArea_{CDC} - \left(DCCordRightArea_{CDC} - DCCordLeftArea_{CDC}\right)$$

Constraint for maintaining equal flow path length

$$OCDCCentralAxis = \left(\left(R - \left(DCCordWidth_{CDC} / 2\right) - DCCordWidth_{SDC}\right) / 2 \right) + DCCordWidth_{SDC}$$

Constraints for area and cord width of the off-center downcomer

$$DCCordPosLeft_{OCDC} = OCDCCentralAxis - \left(DCCordWidth_{OCDC} / 2.\right)$$

$$DCCordPosRight_{OCDC} = OCDCCentralAxis + \left(DCCordWidth_{OCDC} / 2.\right)$$

$$DCCordPosFromCenterLeft_{OCDC} = R - DCCordPosLeft_{OCDC}$$

$$DCCordPosFromCenterRight_{OCDC} = R - DCCordPosRight_{OCDC}$$

$$DCCordThetaLeft_{OCDC} = 2 * arccos\left(DCCordPosFromCenterLeft_{OCDC} / R\right)$$

$$DCCordThetaRight_{OCDC} = 2 * arccos\left(DCCordPosFromCenterRight_{OCDC} / R\right)$$

$$DCCordLeftArea_{OCDC} = \left(\left(R^2 \right) / 2 \right) * \left(DCCordThetaLeft_{OCDC} - sin \left(DCCordThetaLeft_{OCDC} \right) \right)$$

$$DCCordRightArea_{OCDC} = \left(\left(R^2 \right) / 2 \right) * \left(DCCordThetaRight_{OCDC} - sin \left(DCCordThetaRight_{OCDC} \right) \right)$$

$$0 = DCArea_{OCDC} - \left(DCCordRightArea_{OCDC} - DCCordLeftArea_{OCDC} \right)$$

Constraints for sloping considerations

$$Slope = DCCordWidth_{SDC} - DCBottomCordWidth_{SDC}$$

$$DCBottomCordWidth_{CDC} = DCCordWidth_{CDC} - 2 * Slope$$

$$DCBottomCordWidth_{CDC} = DCCordWidth_{CDC} - 2 * Slope$$

Constraints for panel areas

$$PanLeftCordPos_{S1} = DCCordWidth_{SDC}$$

$$PanRightCordPos_{S1} = OCDCCentralAxis - DCBottomCordWidth_{OCDC} / 2$$

$$PanLeftCordPos_{S2} = OCDCCentralAxis + DCBottomCordWidth_{OCDC} / 2$$

$$PanRightCordPos_{S2} = R - DCCordWidth_{CDC} / 2$$

$$PanLeftCordPos_{S3} = DCBottomCordWidth_{SDC}$$

$$PanRightCordPos_{S3} = OCDCCentralAxis - DCCordWidth_{OCDC} / 2$$

$$PanLeftCordPos_{S4} = OCDCCentralAxis + DCCordWidth_{OCDC} / 2$$

$$PanRightCordPos_{S4} = R - DCBottomCordWidth_{CDC} / 2$$

$$PanAreaPosFromCenterLeft_{panel} = R - PanLeftCordPos_{panel}$$

$$PanAreaPosFromCenterRight_{panel} = R - PanRightCordPos_{panel}$$

$$PanAreaThetaRight_{panel} = 2 * arccos \left(PanAreaPosFromCenterRight_{panel} / R \right)$$

$$PanAreaLeftArea_{panel} = \left(R * R / 2 \right) * \left(PanAreaThetaLeft_{panel} - sin \left(PanAreaThetaLeft_{panel} \right) \right)$$

$$PanAreaRightArea_{panel} = \left(R * R / 2 \right) * \left(PanAreaThetaRight_{panel} - sin \left(PanAreaThetaRight_{panel} \right) \right)$$

$$PanArea_{panel} = PanAreaRightArea_{panel} - PanAreaLeftArea_{panel}$$

V. Results and Discussion

The above model was solved using GAMS for any input for the side downcomer width and then the results we get from the GAMS output are taken as input into a calculator made in python for further analysis of the results obtained from GAMS for calculating parameters that would confirm that objectives we originally desired to achieve have been achieved.

GAMS results would provide us with the following

(i) Side downcomer widths of all the downcomers (top and bottom)
(ii) Off-Center downcomer center axis position
(iii) Weir Lengths

The results obtained from GAMS have also been use an input into a commercial tray rating software Sulcol 3.0 which is a Sulzer Design Program for Structured and Random Packings, and Trays in order to analyze the results and confirm the achievement of our objectives discussed previously.

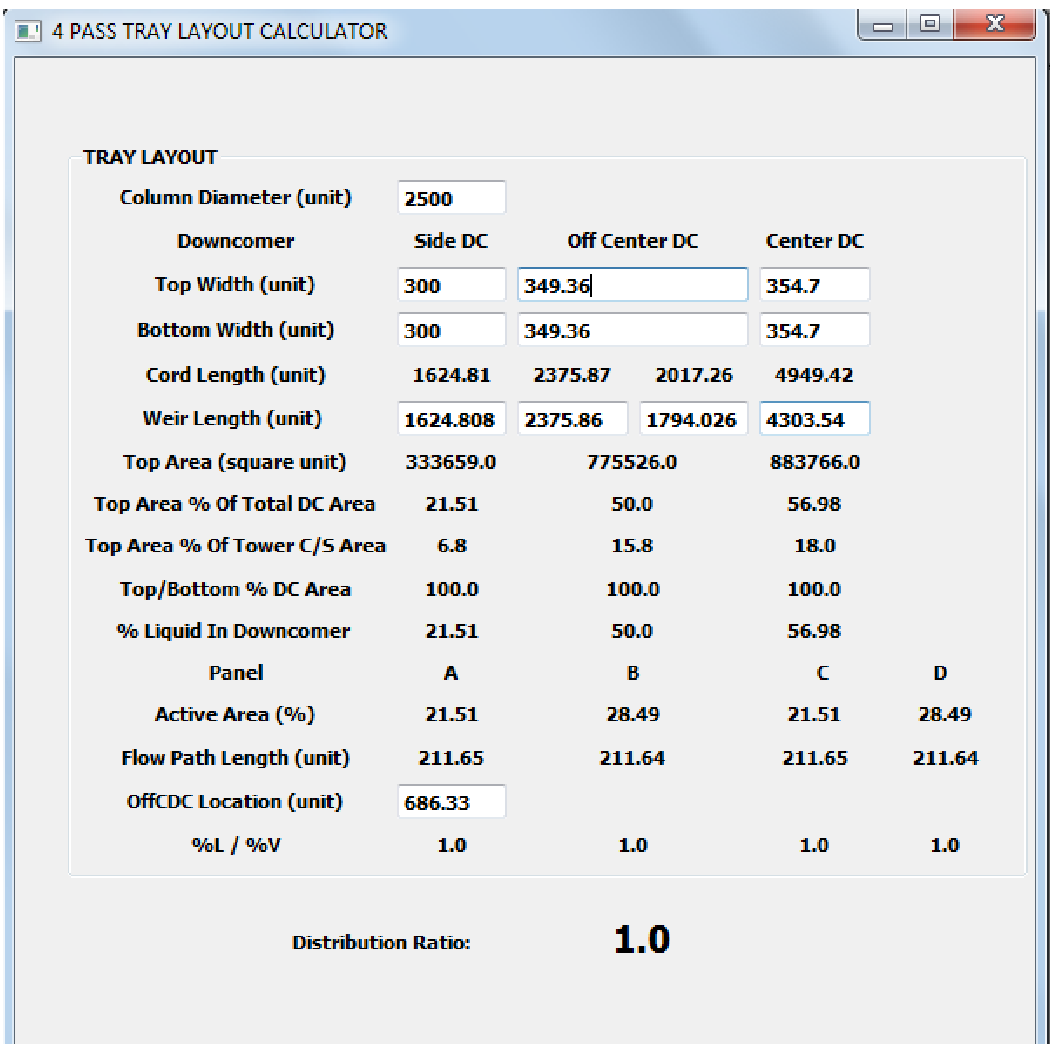
Two examples of using a straight downcomer and sloped downcomers respectively have been optimized and the results of that optimization have been shown below.

Example 1: Choosing a diameter of column = 2500 mm, with a side downcomer cord width of 300mm and no sloping.

GAMS Results:

Column Diameter(mm)	2500			
Downcomer	Side	Off-Center		Center
Top Cord Width(mm)	300	349.36		354.7
Bottom Cord Width(mm)	300	349.36		354.7
Weir Length(mm)	1624.8	2375.87	1794	4303.59
OffCented DC Axis(mm)	686.327			

Further analysis from python:


4 PASS TRAY LAYOUT CALCULATOR

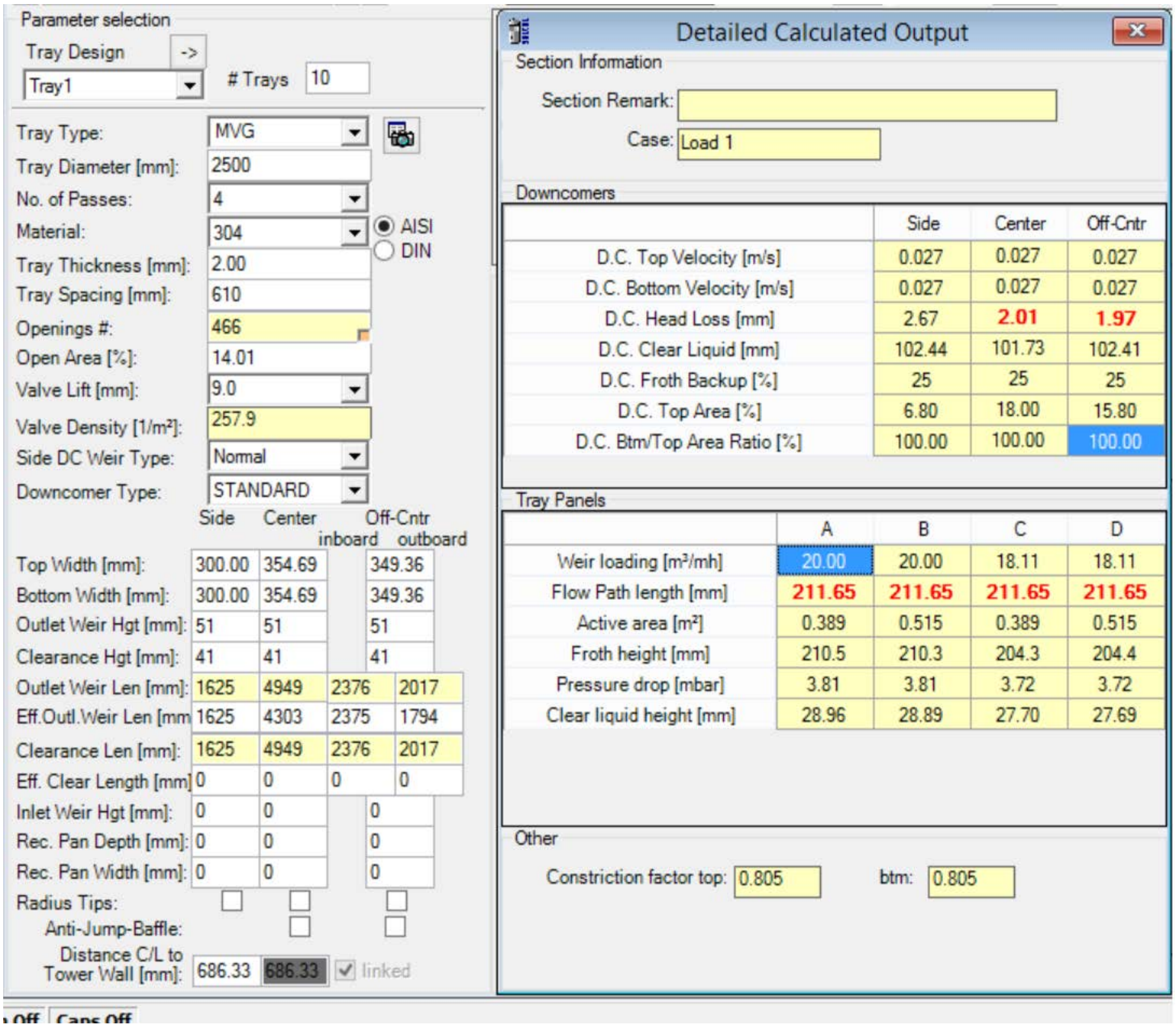
TRAY LAYOUT

Column Diameter (unit)	2500			
Downcomer	Side DC	Off Center DC		Center DC
Top Width (unit)	300	349.36		354.7
Bottom Width (unit)	300	349.36		354.7
Cord Length (unit)	1624.81	2375.87	2017.26	4949.42
Weir Length (unit)	1624.808	2375.86	1794.026	4303.54
Top Area (square unit)	333659.0	775526.0		883766.0
Top Area % Of Total DC Area	21.51	50.0		56.98
Top Area % Of Tower C/S Area	6.8	15.8		18.0
Top/Bottom % DC Area	100.0	100.0		100.0
% Liquid In Downcomer	21.51	50.0		56.98

Panel	A	B	C	D
Active Area (%)	21.51	28.49	21.51	28.49
Flow Path Length (unit)	211.65	211.64	211.65	211.64
OffCDC Location (unit)	686.33			
%L / %V	1.0	1.0	1.0	1.0

Distribution Ratio: **1.0**

Sulcol 3.0.8 Output



The GAMS and python output shows us that we have achieved a distribution ratio of 1.0 for the given straight downcomer. The inlet velocities are also the same as the given % downcomer area is equal to the % liquid in the downcomer.

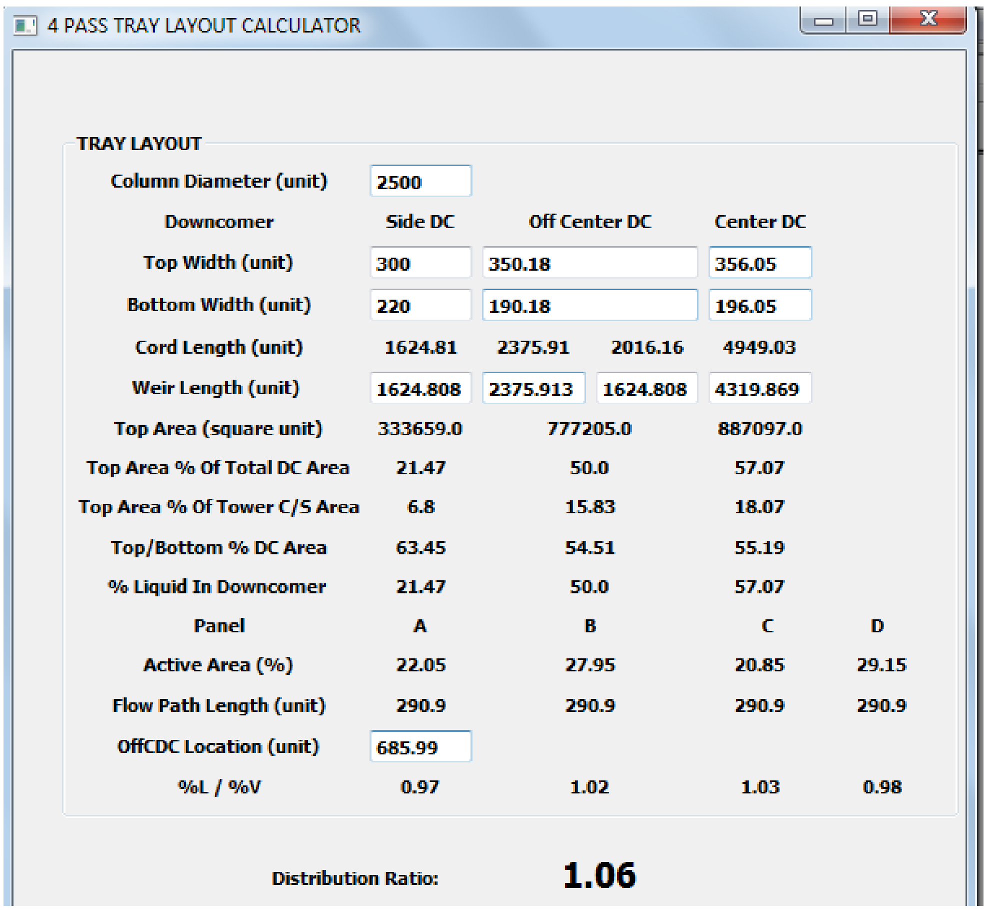
The Sulcol output also shows us that the pressure drop on each panel is uniform and so are the weir loads the same for the center and side downcomer as well as for either side of the off-center downcomer which were desired results after optimizing the tray layout for minimum mal-distribution.

Example 2: Choosing a diameter of column = 2500 mm, with a side downcomer cord width of 300mm and 80 mm of sloping.

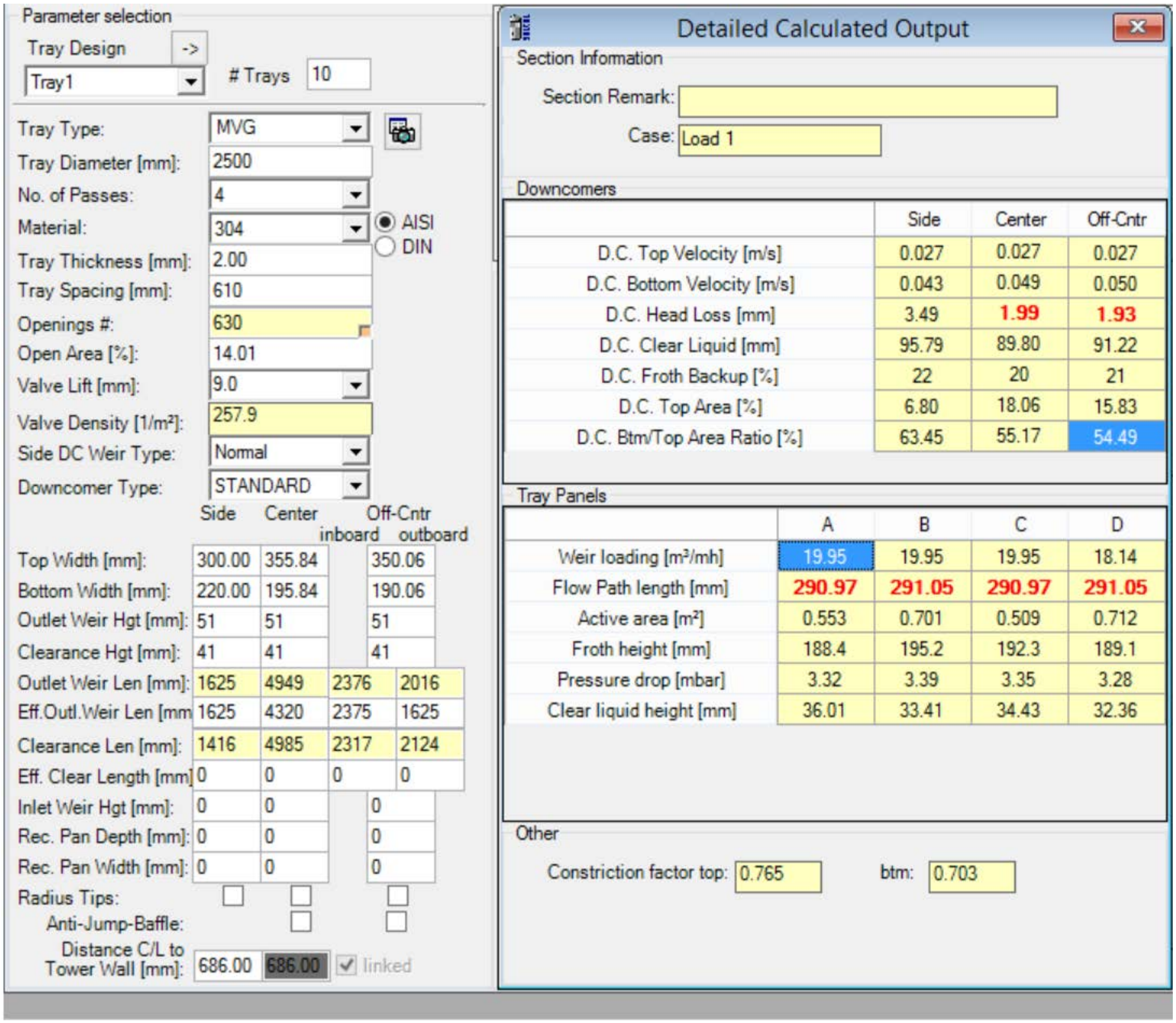
GAMS Results:

Column Diameter(mm)	2500			
Downcomer	Side	Off-Center		Center
Top Cord Width(mm)	300	350.18		356.05
Bottom Cord Width(mm)	220	190.18		196.05
Weir Length(mm)	1624.8	2375.87	1624.8	4319.03
OffCenter DC Axis(mm)	685.988			

Further analysis in python:



Sulcol 3.0.8



The GAMS and python output shows us that we have achieved a distribution ratio of 1.06 which is within the criterion suggested by Summers [1] for the given highly sloped downcomer. The inlet velocities are also the same as the given % downcomer area is equal to the % liquid in the downcomer.

The Sulcol output also shows us that the pressure drop on each panel is uniform and so are the weir loads the same for the center and side downcomer as well as for either side of the off-center downcomer which were desired results after optimizing the tray layout for minimum mal-distribution.

VI. Conclusion and Future Work

The optimization model proposed would ensure that the tray's vapor and liquid loads would be inherently balanced giving a distribution ratio of 1.0 for straight downcomers and a distribution ratio as close to 1.0 as possible for sloped downcomers as can been seen in the above results.

Future work:

- This tray layout optimization could be embedded in a pressure drop minimization program given a pressure drop model for any type of tray.

- This could be extended to other multi-pass trays (3 or 6 pass trays) without much extra effort even though these trays are rarely used now. Kister et al. [3] has suggested that in recent times economics has favored towers with large diameters of greater than 20-30 feet, which could potentially require using greater than 6 pass trays.

VII. References

1. Summers, D. R., Chem. Eng. Progr., p.26, April (2010)
2. Bolles, W., AIChE J, 22 (1), 153, (1976)
3. Kister, H. Z., R. W. Dionne, W. J. Stupin, and M. Olsson, Chem. Eng. Progr., p.32, April (2010)